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Group H: Expandable Brush

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Washington University in St. Louis

SCHOOL OF ENGINEERING & APPLIED SCIENCE

This is an overview of our project to design an expandable brush. This brush is designed to be versatile and able to clean a variety of vessels with narrow necks, wide bases, and complex geometries. Our prototype consisted of two parts: an outer sleeve with a deflector and a handle with a head piece to hold our bristle filaments. This design allows the user to insert the brush into a vessel and then control how far outward the bristles expand for easy cleaning.

MEMS 411

Design

Expandable Brush

Aaron Hall & Michael Roznik

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1 INTRODUCTION

1.1 PROJECT PROBLEM STATEMENT

Fine restaurants around the world look for ways to make their venue unique and memorable. One way they do this is by using custom serving wares. In particular, artistic wine carafes are very common. However, the unique designs of these carafes can make cleaning them a chore. Our design is an expandable brush for scrubbing the inside of carafes and other shaped glassware. The brush will start as a compact cylinder that is inserted into the neck of the glassware. We will then incorporate a mechanism that allows the user to expand the brush's bristles to reach to the sides of the glassware for a more thorough clean. This would provide superior cleaning ability to flimsy wire brushes.

1.2 LIST OF TEAM MEMBERS

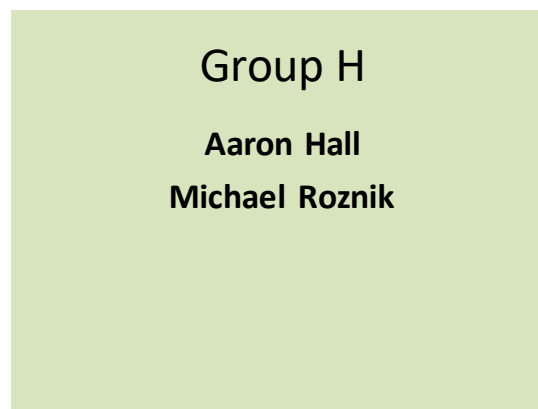


Fig. 1 Group H: Expandable Brush is composed of Aaron Hall and Michael Roznik

2 BACKGROUND INFORMATION STUDY – CONCEPT OF OPERATIONS

2.1 A SHORT DESIGN BRIEF DESCRIPTION THAT DESCRIBES THE PROBLEM

Currently, the most significant risk for our design process is going to be designing a device that incorporates reliable use and a small enough size. With our design, we need to keep the mechanism simple to allow for successful scaling. Since we will be 3D printing our design, maintaining clearances at the necessary size will be a challenge. Our brush design needs to be producible at a small enough size that it can fit into a variety of vessels for cleaning to solve the problem we are trying to address.

2.2 SUMMARY OF RELEVANT BACKGROUND INFORMATION

The following figures are screen shots are from an initial websearch of products that aim to clean decanters.

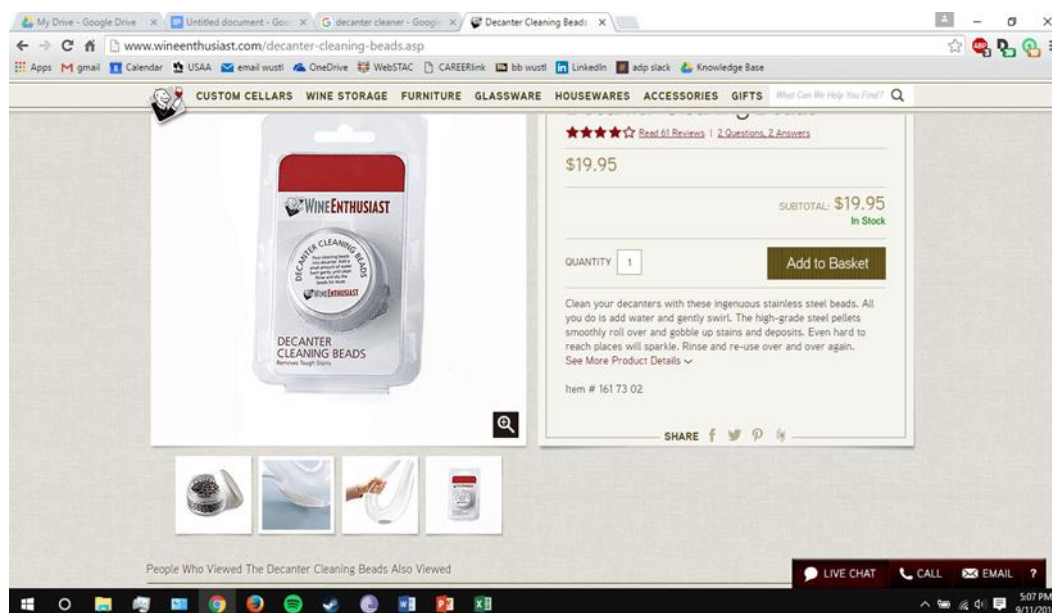


Fig. 2 *Wine Enthusiast's ball bearings for decanter cleaning.*



Fig. 3 *Cuisipro's magnetic decanter cleaning device.*

3 CONCEPT DESIGN AND SPECIFICATION – DESIGN REQUIREMENTS

3.1 OPERATIONAL REQUIREMENTS ALLOCATED AND DECOMPOSED TO DESIGN REQUIREMENTS

3.1.1 Trees of identified operational and design requirements

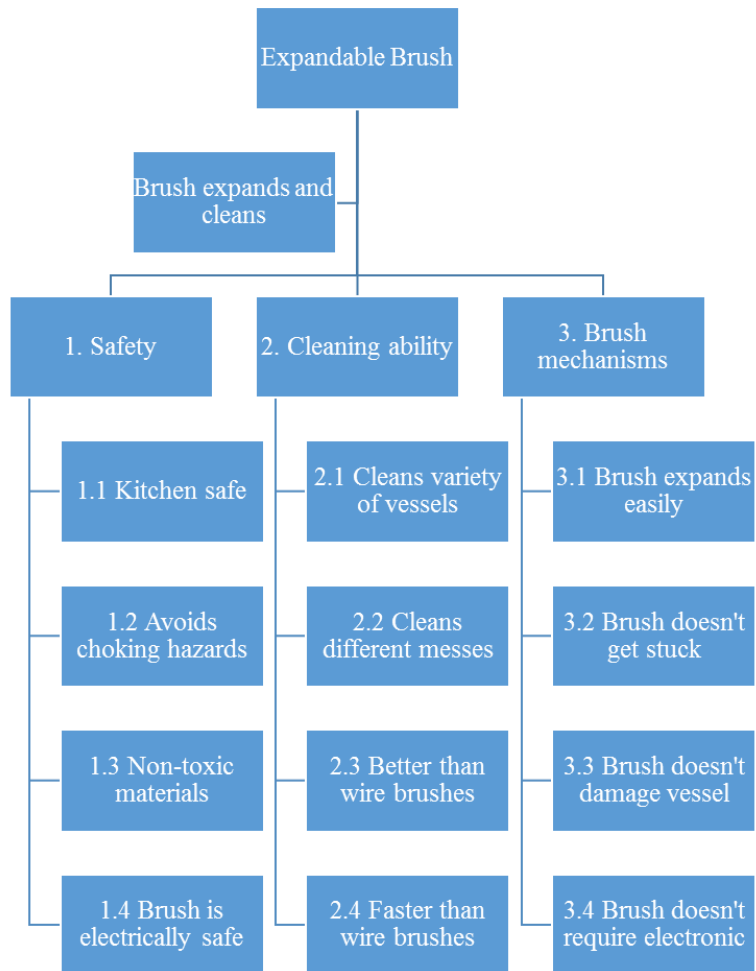


Fig. 4 Operational requirement tree.

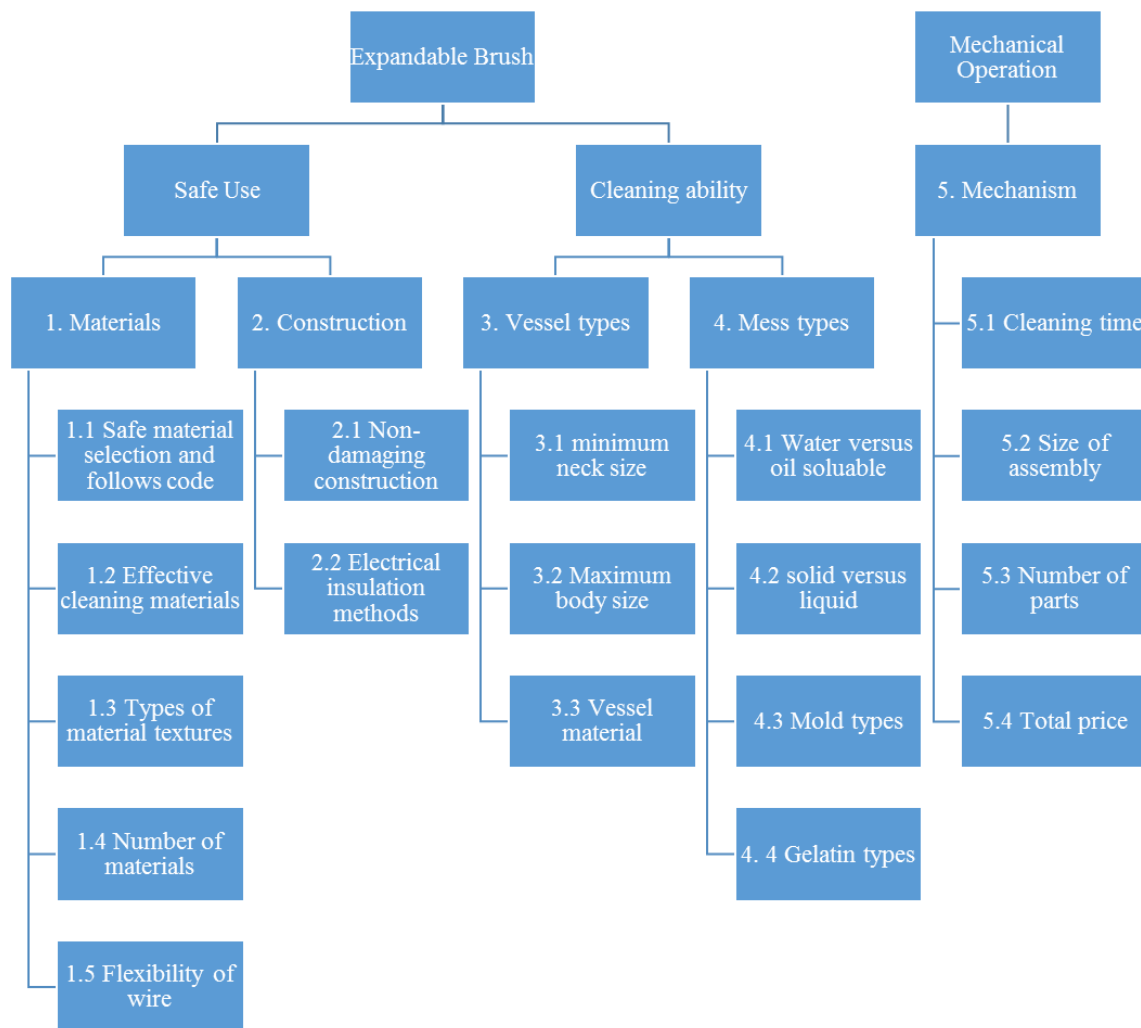


Fig. 5 Design requirement tree

3.1.2 Functional allocation and decomposition

Outer Sleeve: serves as the housing for our brush. This part will define the minimum diameter our brush can fit through

Deflector: this part is attached at the base of the outer sleeve and will deflect the bristles outward radial

Brush head: is attached to a handle and holds the bristle filaments. This part will need to be able to fit and move within the outer sleeve

Bristle filament: attached within the brush head and will be deflected outward by the deflector. These parts will perform the scrubbing action of the brush

Handle: attached to the brush head and allows the user to push the bristles into the deflector

3.2

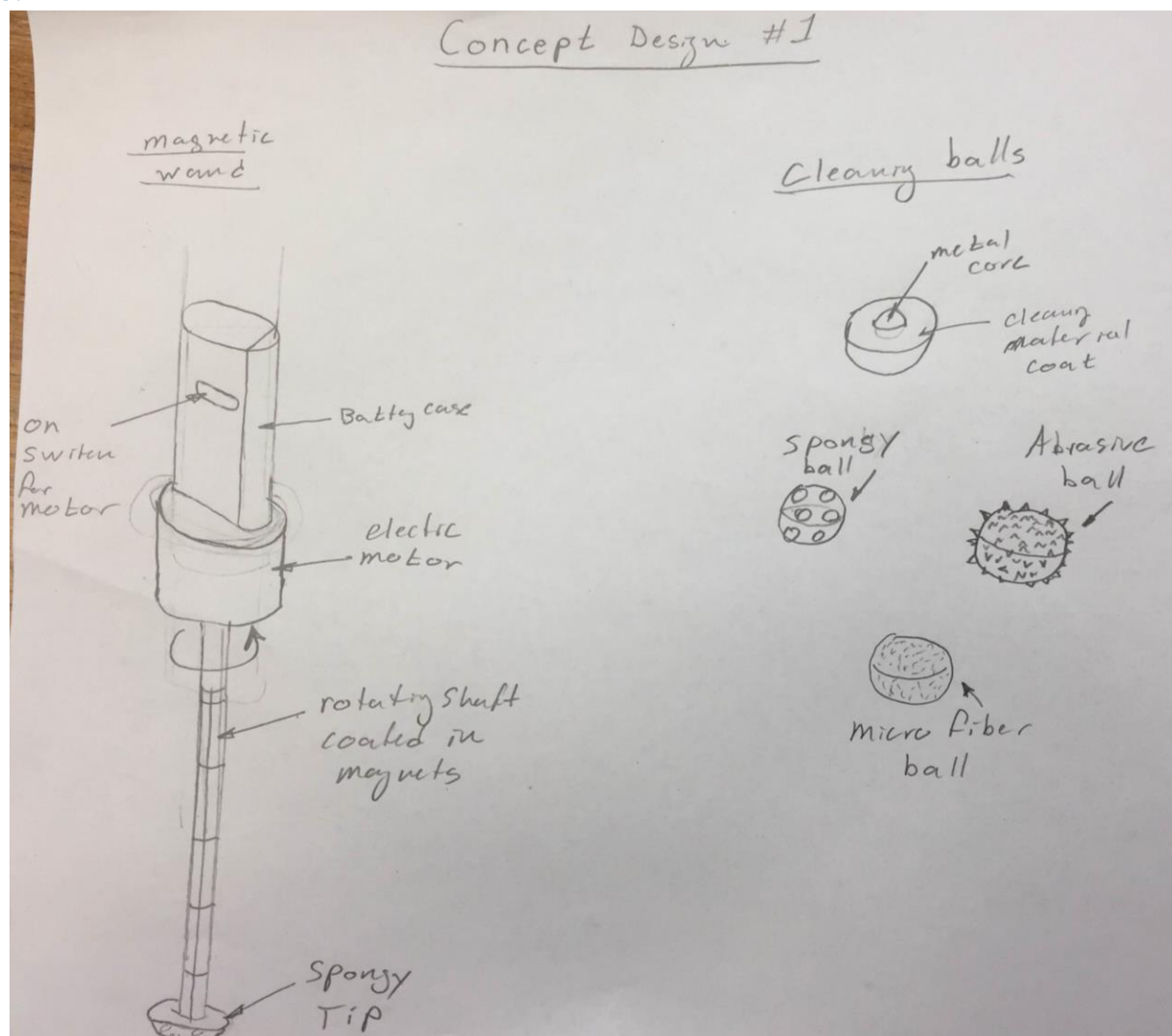


Fig. 6 Balls with magnetic wand concept drawing

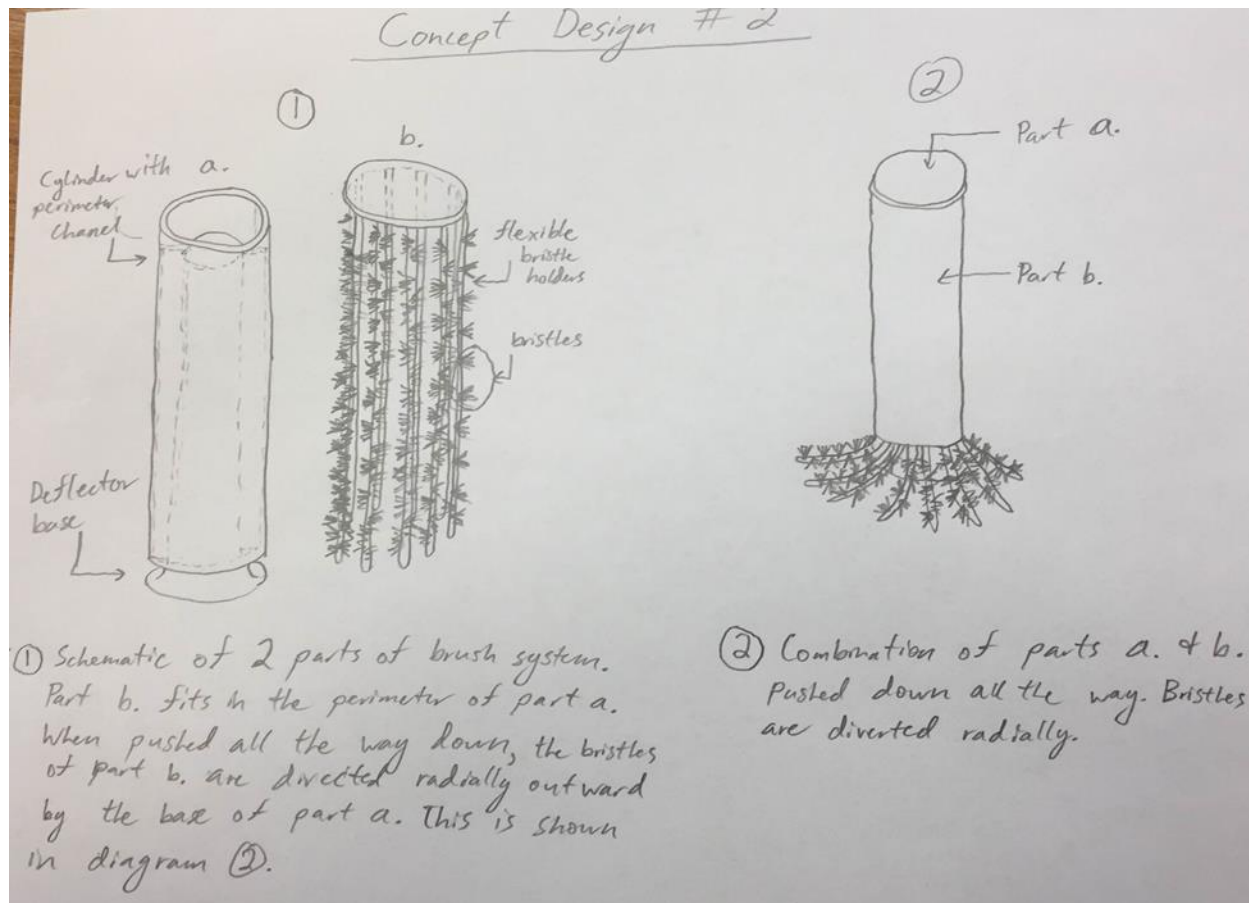


Fig. 7 Expanding brush concept drawing.

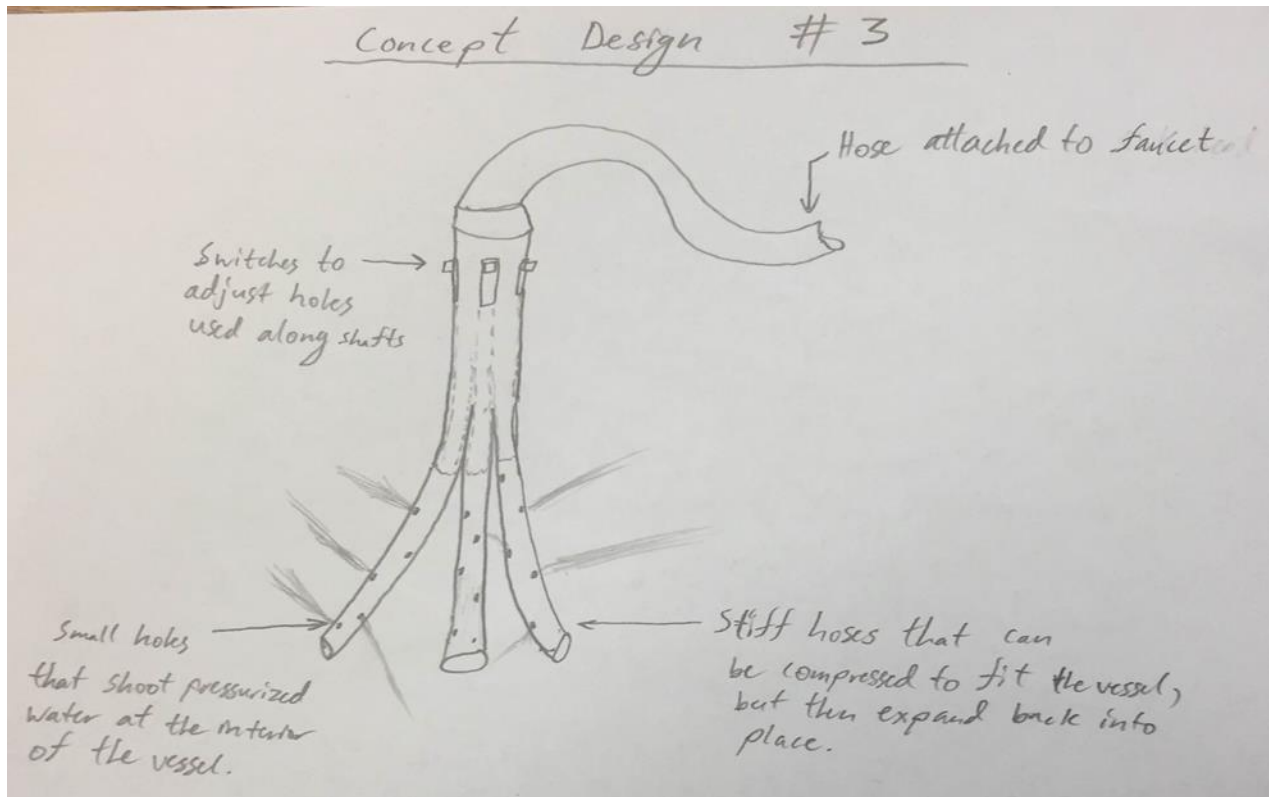


Fig. 8 Hydraulic cleaning tube concept drawing

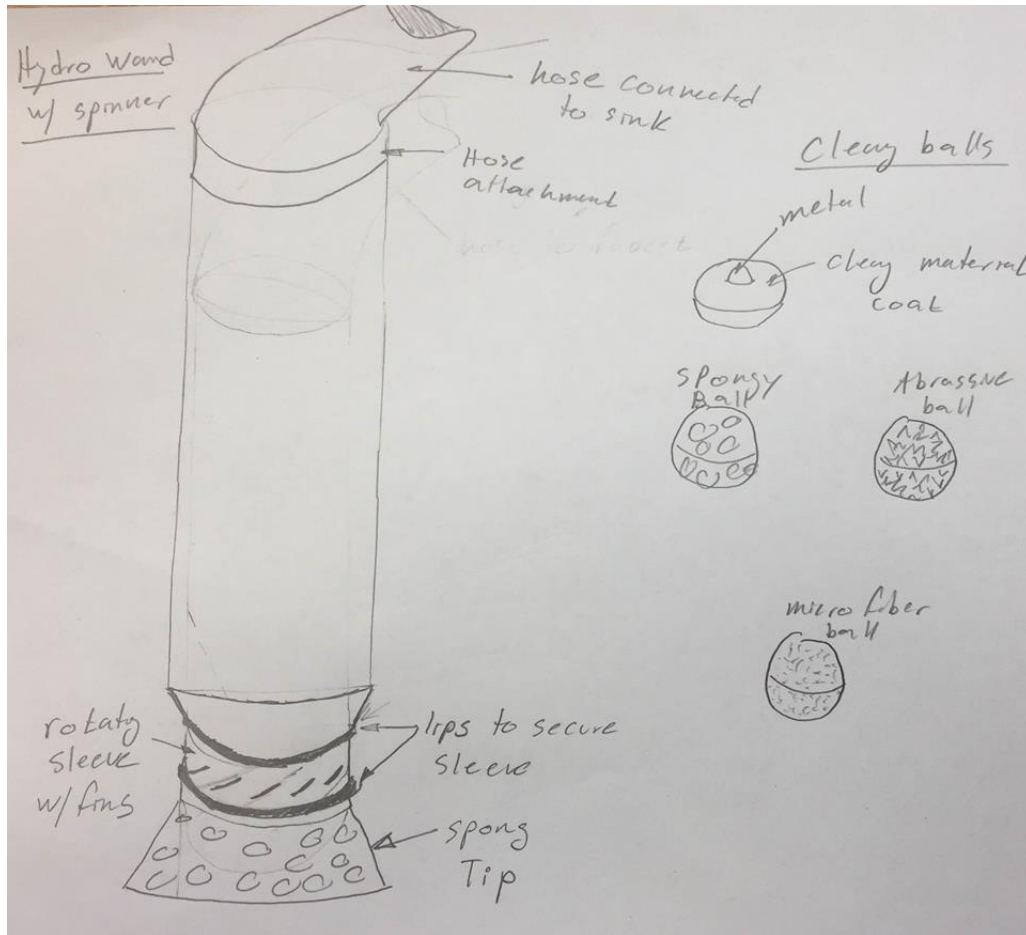


Fig. 9 Balls with hydraulic agitation concept drawing.

3.3 CONCEPT SELECTION PROCESS

3.3.1 Preliminary analysis of each concept's physical feasibility based on design requirements, function allocation, and functional decomposition

Balls with magnetic wand: The benefit of the magnetic wand is that the ball size is the only limiting factor for the minimum vessel neck size. In other words, the smallest neck size that could be cleaned is only determined by the size of the largest balls. A large draw back from the magnetic wand solution is that strong magnets are expensive. This large cost has a significant impact on this solution's feasibility. Additionally, the strength of the magnetic field generated is proportional to r^2 . Thus, the decay in strength is exponentially negative. This raises significant concerns for the magnetic force's ability to agitate the balls enough to produce significant cleaning motion. On the other hand, the magnetic wand design could offer the most compact option for cleaning vessels with small necks and large bodies. This is because the wand could be used on the inside or outside of the vessel to magnetically cause motion in the cleaning balls.

Expanding brush: This design incorporates two separate pieces that, once combined, can adjust bristles to various radii. The outer sleeve is a hollow cylinder with an insert attached in the middle. At the bottom, the insert flairs outward. The bristles in this design are removable from the system. These bristles are attached along the outer perimeter of part b. in the concept drawing shown in Fig. 5. This allows for part b. to be inserted into part a. When part b. is pressed down inside part a. the bristles are deflected by the bottom insert and extend outward. The extension length of the bristles is adjusted by changing the height of part b. In order for this design to work, the bristles need to be flexible enough to bend when deflected by the base, but also rigid enough to maintain a perpendicular position once deflected. One advantage of this design is its simplicity and ease of replaceable parts. Because the bristle component is removable, cleaning of the components is also easy. However, this design is manual and would require a person to change and move the brush around the vessel. It will also be difficult to find a suitable material for the bristle holders because they must be very thin. This brush will also only be able to reach relatively common shapes with narrow necks and wide bases because the bristles can only extend perpendicular to the outer cylinder's base.

Hydraulic cleaning tube: This design uses water and pressure to create a forceful stream that would clean the inside of a vessel. A hose would need to connect the device to a sink or faucet head. This water flow would then be distributed to three or four semi-flexible hoses. These hoses will be a resilient material that will allow the user to bunch them together for insertion. Once inside, the hoses will expand back to their extended positions. The hoses have a number of small holes along them to allow water to be sprayed out in forceful streams. There are also adjusters toward the top of the device that will allow the user to cover up holes as needed in order to increase the force of the streams towards the bottom. The advantage of this design is it will not get dirty while cleaning the vessel, which makes it very reusable. It also only uses water to clean, so there are less issues with material selection. One issue with this design is that there is no component to collect the waste after it has been removed from the walls of the vessel, which could re-adhere to the walls. There is also the issue of designing a hose that will be universal for all faucet head types.

Balls with hydraulic agitation: This design represents a combination of the hydraulic cleaning tube and the magnetic wand alternatives. Instead of using magnetic forces to move cleaning balls around the body of a small necked vessel, this solution uses the velocity of water exiting a rotating sleeve on the head of the device. This rotating sleeve has internal angled tubes that spin as water exits the wand. The benefits of this is that there is no cost of magnets. Unfortunately, the possible strength of the water may still not provide adequate agitation for the cleaning balls to work. Additionally, using water to propel and agitate the balls will cause the vessel to fill with water which would slow down the movement of the cleaning balls.

3.3.2 Concept scoring

| Metric Number | Associated Needs | Metric | Units | Min Value | Max Value | Actual Value | Normalized Value |
|---------------|------------------|------------------|----------|-----------|-----------|--------------|------------------|
| 1 | 3, 5 | Diameter | mm | 10 | 25 | 15 | -0.333 |
| 2 | 3, 5 | Length | mm | 150 | 300 | 300 | 1.000 |
| 3 | 1, 2 | Food Safe | Binary | 0 | 1 | 1 | 1.000 |
| 4 | 3, 4, 5 | Cleaning Ability | Scale | 1 | 5 | 2.5 | 0.375 |
| 5 | 5 | Cleaning Time | Sec. | 5 | 300 | 120 | -0.390 |
| 6 | 1, 2 | Cost | USD (\$) | 1 | 150 | 120 | -0.799 |
| | | | | | | TOTAL | 0.853 |
| | | | | | | | |
| Metric Number | Associated Needs | Metric | Units | Min Value | Max Value | Actual Value | Normalized Value |
| 1 | 3, 5 | Diameter | mm | 10 | 25 | 25 | -1.000 |
| 2 | 3, 5 | Length | mm | 150 | 300 | 200 | 0.333 |
| 3 | 1, 2 | Food Safe | Binary | 0 | 1 | 1 | 1.000 |
| 4 | 3, 4, 5 | Cleaning Ability | Scale | 1 | 5 | 3.5 | 0.625 |
| 5 | 5 | Cleaning Time | Sec. | 5 | 300 | 120 | -0.390 |
| 6 | 1, 2 | Cost | USD (\$) | 1 | 150 | 70 | -0.463 |
| | | | | | | TOTAL | 0.105 |
| | | | | | | | |
| Metric Number | Associated Needs | Metric | Units | Min Value | Max Value | Actual Value | Normalized Value |
| 1 | 3, 5 | Diameter | mm | 10 | 25 | 25 | -1.000 |
| 2 | 3, 5 | Length | mm | 150 | 300 | 240 | 0.600 |
| 3 | 1, 2 | Food Safe | Binary | 0 | 1 | 1 | 1.000 |
| 4 | 3, 4, 5 | Cleaning Ability | Scale | 1 | 5 | 1.5 | 0.125 |
| 5 | 5 | Cleaning Time | Sec. | 5 | 300 | 180 | -0.593 |
| 6 | 1, 2 | Cost | USD (\$) | 1 | 150 | 100 | -0.664 |
| | | | | | | TOTAL | -0.533 |
| | | | | | | | |
| Metric Number | Associated Needs | Metric | Units | Min Value | Max Value | Actual Value | Normalized Value |
| 1 | 3, 5 | Diameter | mm | 10 | 25 | 25 | -1.000 |
| 2 | 3, 5 | Length | mm | 150 | 300 | 300 | 1.000 |
| 3 | 1, 2 | Food Safe | Binary | 0 | 1 | 1 | 1.000 |
| 4 | 3, 4, 5 | Cleaning Ability | Scale | 1 | 5 | 3 | 0.500 |
| 5 | 5 | Cleaning Time | Sec. | 5 | 300 | 120 | -0.390 |
| 6 | 1, 2 | Cost | USD (\$) | 1 | 150 | 80 | -0.530 |
| | | | | | | TOTAL | 0.580 |

Table 1. Design metrics template. Scores are listed in the following order from top to bottom: balls with magnetic wand, expanding brush, hydraulic cleaning tube, balls with hydraulic agitation.

3.3.3 Design requirements for selected concept

We have selected the Expanding Brush design. These design requirements will be the same as the listed requirements in Fig. X above.

3.3.4 Final summary

Our first iteration is a two-part design. The first part is an outer sleeve with a deflector attached at one end. The second part is a device to hold our bristles attached to some sort of rod to allow the user to push this device through the outer sleeve. This full device will be inserted into the neck of the bottle and then the rod can be pushed to disperse the bristles radially to a desired distance. The brush can then be used to scrub and clean the inside of the vessel. Once the cleaning is completed the bristles can retract to allow for easy removal from the vessel.

The performance goals that we have chosen to assess our design are:

1. Clean all types of mess (water soluble and oil soluble)
2. Reliable (mechanism constantly expands bristles as desired)
3. Reusable
4. Food safe
5. Follow project budget
6. Must fit into a neck with diameter of 2 in. or smaller
7. Must be able to clean 10 in. downward into a vessel
8. Cleaning time under 5 minutes
9. Brush components easily cleaned

3.4 PROPOSED PERFORMANCE MEASURES FOR THE DESIGN

For our performance measures, we need to select something that is not easily cleaned by hand. It must also be a relatively common item for use with food. For this reason, we selected a wine decanter. A typical wine decanter has a neck opening of less than 2 in. and a height of about 10 in. This is a perfect performance measure because it aligns well with our performance goals. A wine decanter also has a very wide base, which will require good design and execution of our brush for thorough cleaning.

3.5 DESIGN CONSTRAINTS

The wine decanter selected for performance measurement is shown in Figure X.

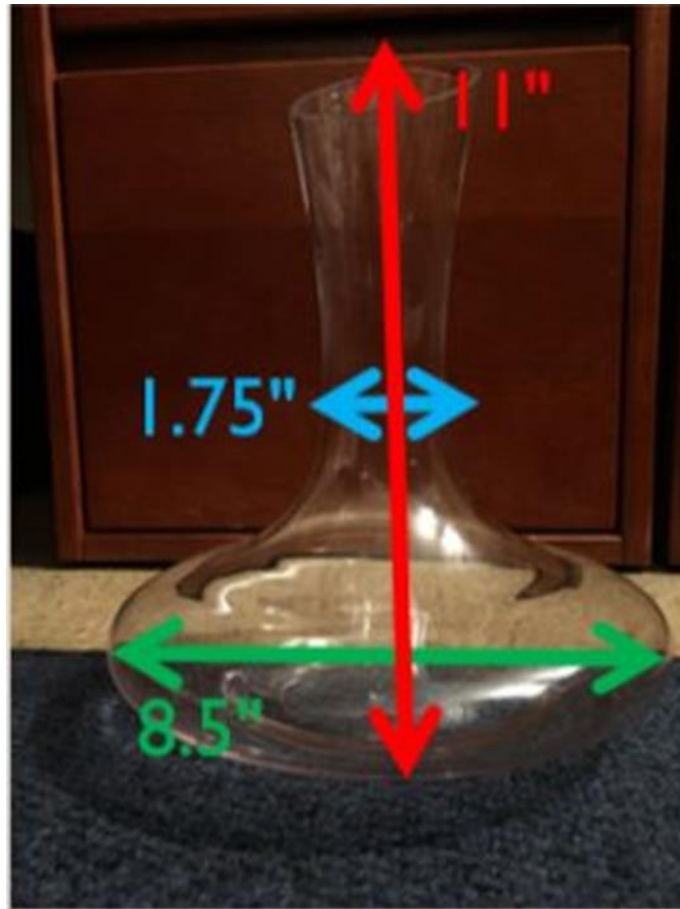


Fig. 10 The wine decanter shown will be used for performance measurement of our expandable brush. It is of glass and has a geometry that make it impossible to clean by hand.

This decanter has a height of 11 in. a base width of 8.5 in. and a neck opening of 1.75 in. All of these dimensions are smaller than our initial performance goals. However, we think that cleaning this vessel is a very good assessment of the brush's design and functionality.

3.5.1 Functional

The device must be able to clean vessels of a variety of shapes and materials. Versatility is very important for our design.

3.5.2 Safety

This brush will likely be used in a domestic setting with food contact. For this reason, we need our brush to be food safe. We also want to avoid any small pieces or materials that may chip so that we can ensure safe usage.

3.5.3 Quality

The brush must be reusable. A one use brush will not meet our performance requirements. For this reason we selecting parts and materials that are sturdy and resilient.

3.5.4 Manufacturing

We must make the brush as simple as possible. Fewer and more simple parts correlate with shorter print times and easy reproducibility.

3.5.5 Timing

If the brush can't clean in a reasonable amount of time, it will not be successful. This brush must clean in a similar timespan to any other cleaning brush.

3.5.6 Economic

A market analysis will be required to understand the full range of the expandable brush's use. So far, people we have met see that the expandable brush can be useful in the domestic settings like kitchens and micro-brewing.

3.5.7 Ergonomic

Ease of use is a big part of the expandable brush. A simple design will be best for everyday users as well as production. The ability to use the brush with one hand would be very beneficial.

3.5.8 Ecological

The materials that this is constructed out of must be dishwasher safe, so that it doesn't harm users or put deadly chemicals into the grey water sewer. The biggest hurdle will be ensuring that the adhesive used is dishwasher safe and ecologically friendly.

3.5.9 Aesthetic

The design of the device must be aesthetically pleasing enough to be stored in a kitchen drawer and used regularly. Current trends in kitchenware use metallic coloring

3.5.10 Life cycle

This constraint goes along with quality. We want our brush to be reusable and reliable. Therefore, we need to suitable materials for production. The brush must be easily taken apart for cleaning. The brush should be designed to be dishwasher safe.

3.5.11 Legal

By keeping this device safe for domestic use, we will abide by multiple regulatory agencies. We will be seeking to meet with the IP office of Washington University in St. Louis to attempt to get ownership of our idea.

4 EMBODIMENT AND FABRICATION PLAN

4.1 EMBODIMENT DRAWING

Assembled Sleeve with Deflector and Brush Handle

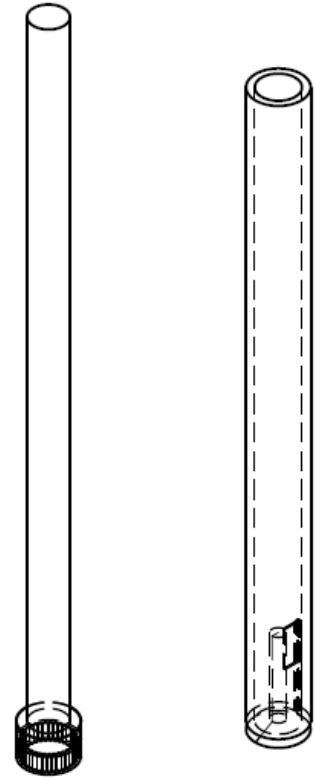


Fig. 11

This is the assembly drawing of the expandable brush with the brush head and handle (left) and the sleeve with the deflector (right)

4.2 PARTS LIST

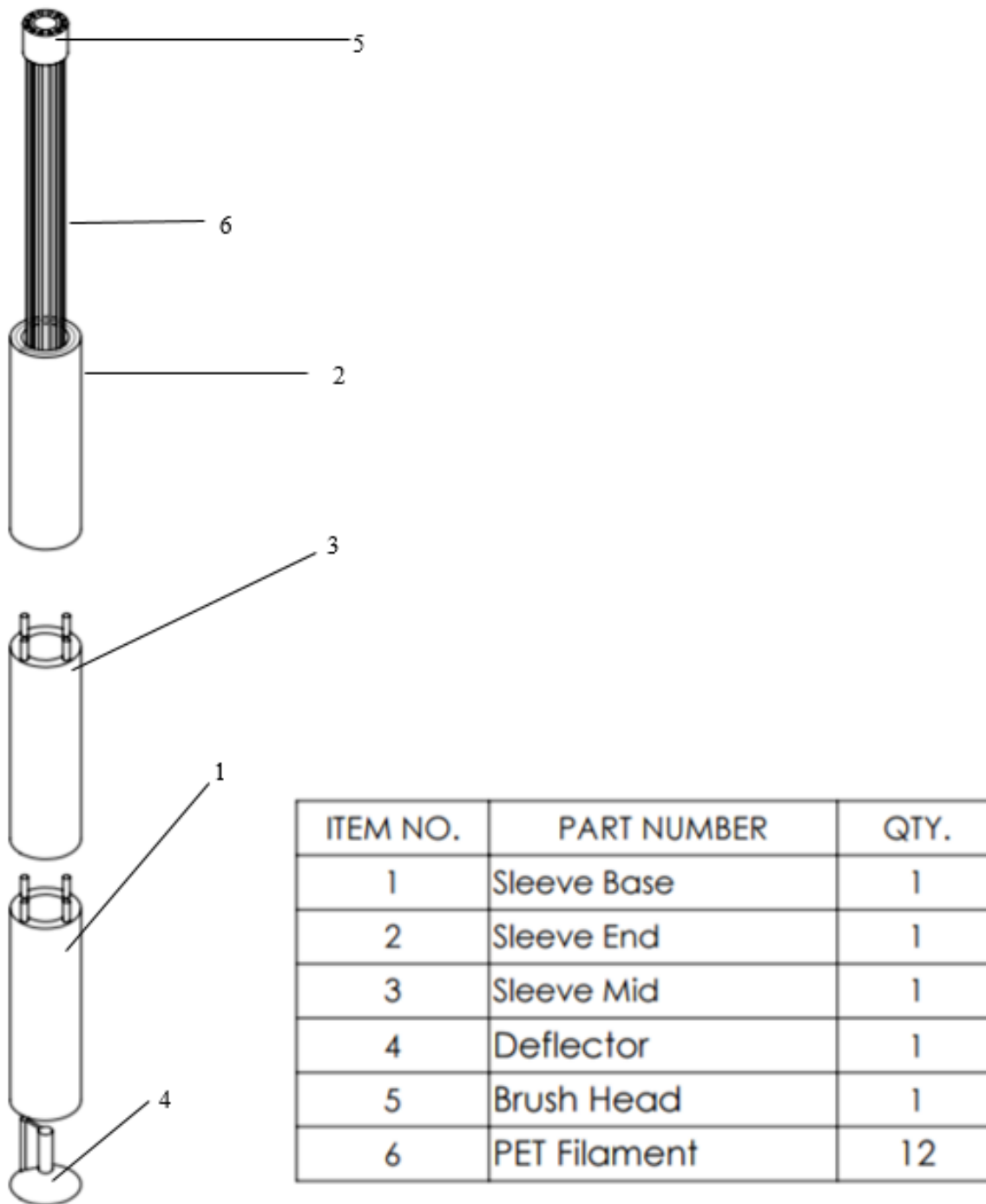


Fig. 12 The exploded view of the assembly that is annotated with the parts list

4.3 DRAFT DETAIL DRAWINGS FOR EACH MANUFACTURED PART

Bristle Handle Drawing

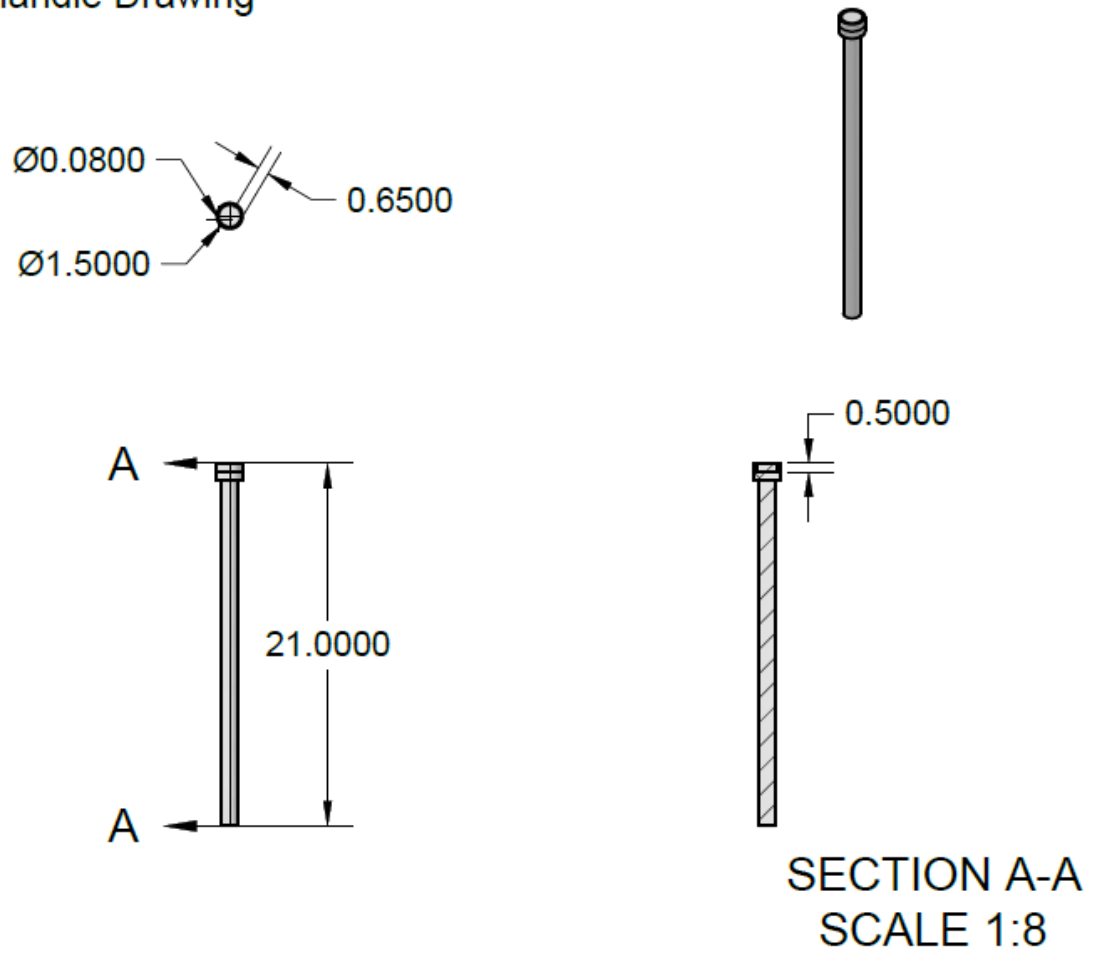


Fig. 13 This is the bristle handle used in the assembly

Outer Cylinder

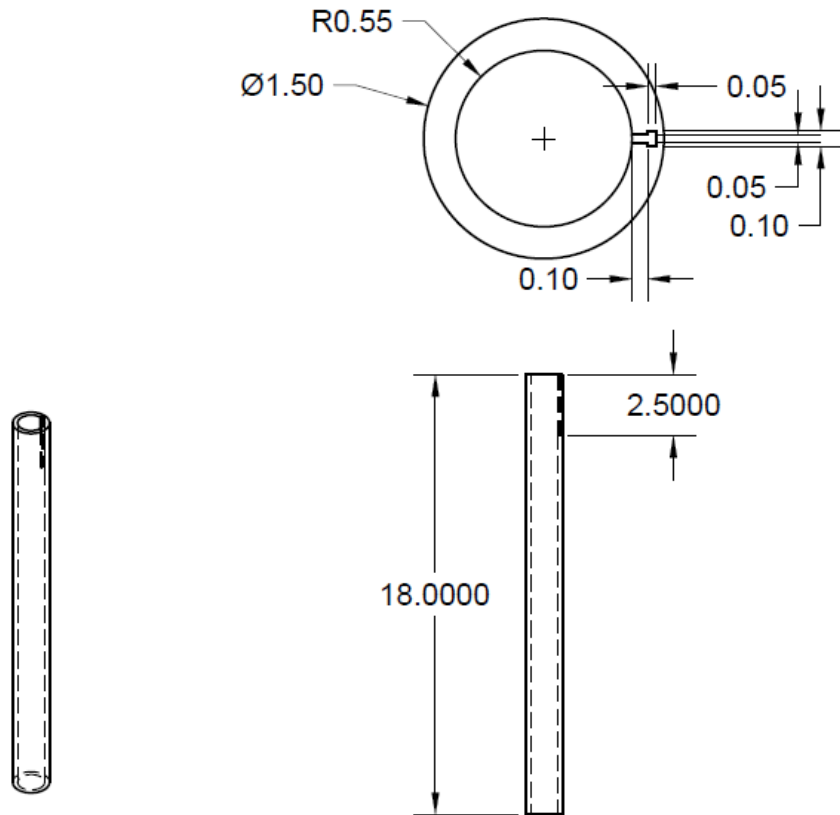


Fig. 14

This is the sleeve used to guide the brush and hold the deflector

Deflector Piece

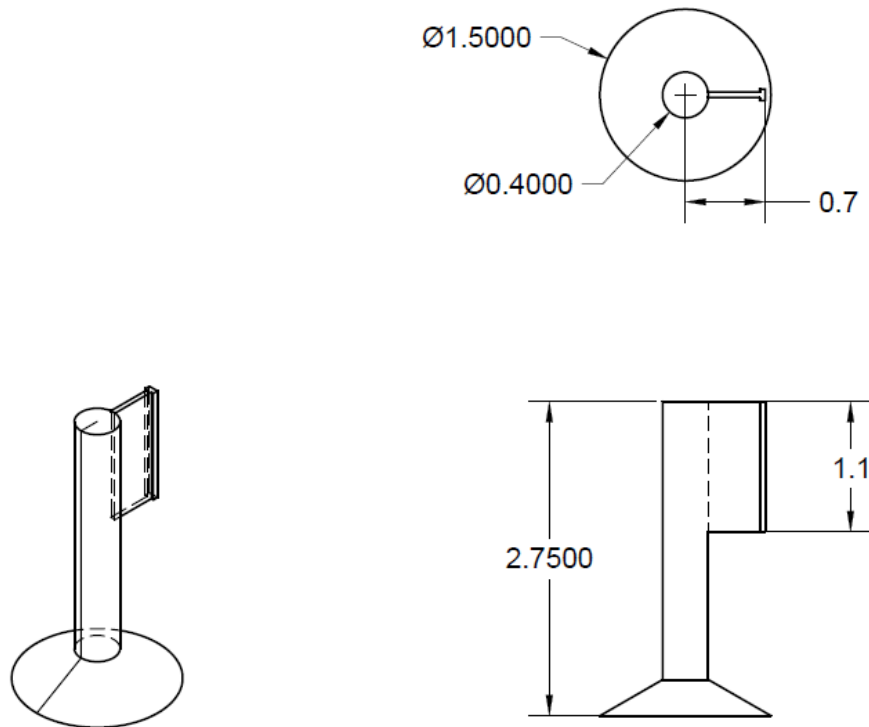


Fig. 15 *This is the first draft of the deflector used in the expandable brush*

4.4 DESCRIPTION OF THE DESIGN RATIONALE FOR THE CHOICE/SIZE/SHAPE OF EACH PART

The sleeve has been chosen to be made 18" long with a key notch on the end. The long length will allow a variety of vessels sizes to be accessed and cleaned by the device. It is currently listed as having a 1.5" diameter in the preliminary drawings. This size will be reduced to 3/4" once the design team has noted all modifications it wishes to complete to the first draft. The key notch will be attached with the tab using epoxy. The sleeve will be 3D printed.

The deflector will be 2.75" long with a conical deflecting end. The cone will push the nylon filament bristles outward to allow cleaning to occur. The deflector has a tab on the cylindrical end that will slide into the key notch and secured there with epoxy, thereby securing the deflector to the sleeve. The deflector will be 3D printed.

The brush handle will be 20" long to ensure that no matter how far down the brushes are pushed, there will always be a handle available for the user to hold on to. At the end of the handle is the plunger like base that will secure the brush bristles. The brush handle will be 3D printed.

The bristles will be approximately 12" long. This will give the brush the ability to expand about 9" radially, enabling it to clean large and complex vessels with skinny necks. Nylon is the primary material which we are investigating right now. These will be ordered in bulk from Alibaba.

4.5 GANTT CHART

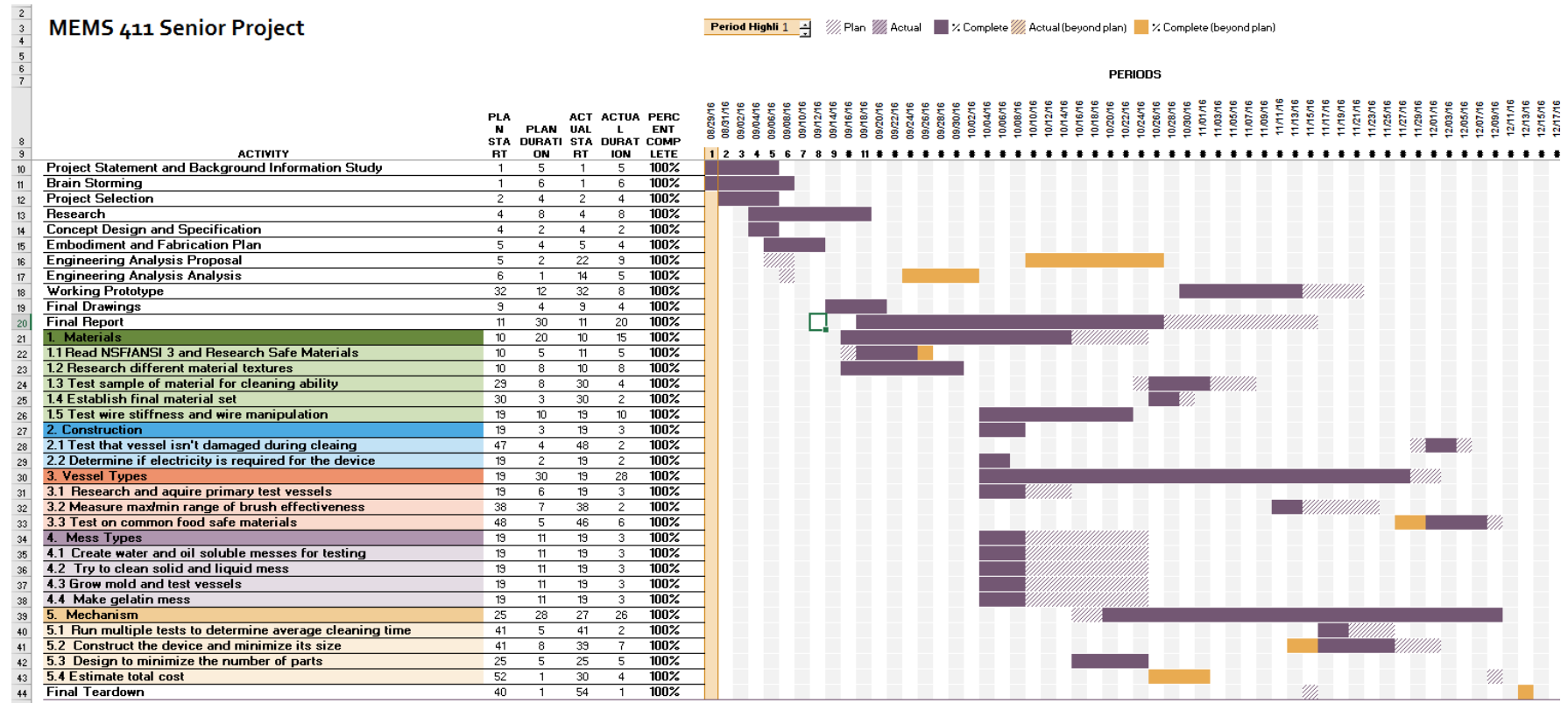


Fig. 16 The Gantt chart used to track the progress of the project and the tasks that needed to be preformed

5 ENGINEERING ANALYSIS

5.1 ENGINEERING ANALYSIS PROPOSAL

5.1.1 A form, signed by your section instructor

This section may be left blank.

5.2 ENGINEERING ANALYSIS RESULTS

5.2.1 Motivation

Describe why and how the analysis chosen is the most important thing to study at this time.

We have chosen two different SolidWorks analyses to study the brush portion of our system. The first is a test of a single brush fiber to ensure that the fiber is stiff enough to clean the inside of our test vessel, a wine decanter, while still having a small size. The stress and deflection were measured in our simulation. We found that PLA and PET Nylon fibers deflected relatively small amounts, making them ideal fibers for our brush.

Our second test modeled the deflection of the brush bristles when they contacted the deflector. It was important to study this to model the angle that our bristles would extend outward from the deflector. It is important to study this aspect of our prototype, because our brush needs to be able to reach upwards to reach hard to clean surfaces once inside the vessel. This was run as a static and dynamic nonlinear simulation. The computer was unable to run it, even on the coarsest mesh settings. No solution could be generated even when consulting with the course instructors.

How does it facilitate carrying the project forward?

These simulations allow us to have confidence in the cleaning ability of our brush and the ability of the assembly to reach upwards to reach hard to clean surfaces.

5.2.2 Summary statement of analysis done

To simulate our brush being pushed against a glass surface to clean we fixed our brush at one end. We then applied an axial force at the opposite end as well as gravity to the entire fiber. We can see in the figure below that a brush bristle with 0.01 N applied axially, a PET fiber only deflects 0.4 mm.

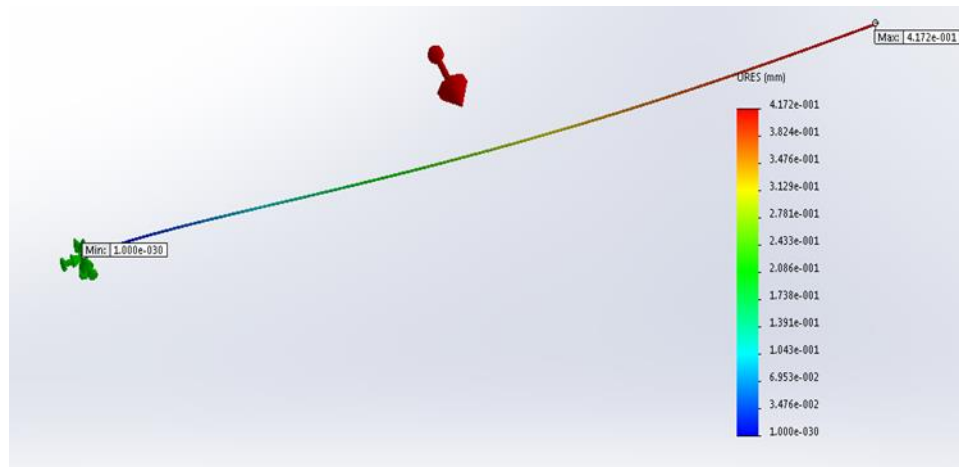


Fig. 17 *A PET fiber undergoing a deformation due to an applied force at the right end and gravity in conjunction with its left end being fixed*

5.2.3 Methodology

How, exactly, did you get the analysis done?

The analysis was carried out with SolidWorks and experimentation.

Was any experimentation required?

Yes, experimentation was used to verify brush cleaning ability. Where our brush contacted was cleaned easily. The biggest issue for us was properly angling the bristles. The deflector angle was varied in experiments to maximize its cleaning ability.

Did you have to build any type of test rig?

We built a prototype and used it to clean wine and other liquid stains from a decanter.

5.2.4 Results

What are the results of your analysis study?

We found through the bristle simulations that PLA and PET filaments worked best by minimizing bristle size and maximizing its stiffness.

Do the results make sense?

These results on SolidWorks were corroborated with our experimentation.

Do the results support moving forward with your current design concept?

The results do indicate moving forward with the material selected. However, we need to lessen the angle and clearance of our deflector to ensure more lateral brush expansion.

5.2.5 Significance

How will the results influence the final prototype, i.e. which differences between the embodiment and final CAD drawings are the result of your engineering analysis?

The results of these studies will validate our material selection and help us redesign our angle and clearance of the deflector to allow the bristles to reach upwards.

What dimensions and material choices will be affected by results of your simulation, if any?

The angular dimension and clearance between the tube and deflector will be altered based on our experimentation and SolidWorks simulations. Primarily, our bristle material selection will be altered based off of our SolidWorks simulation.

This should be shown with some type of revised embodiment drawing. Ideally, you would show a “before/after” analysis pair of embodiment drawings.

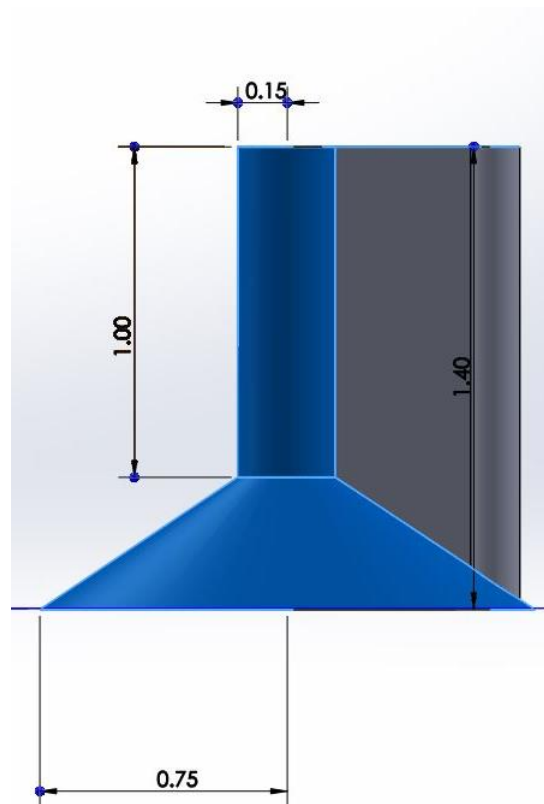


Fig. 18 The original deflector design

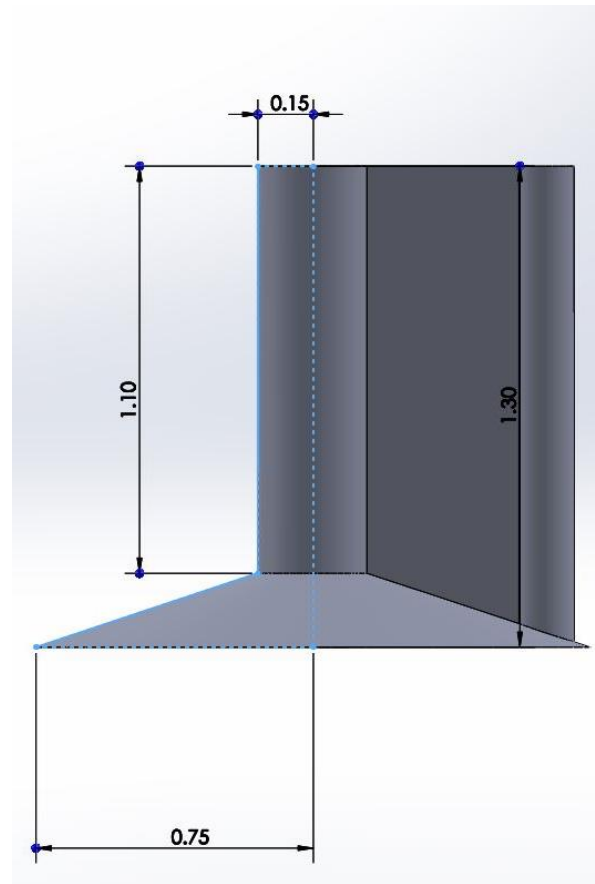


Fig. 19 The new deflector design after the engineering analysis and first prototype

5.2.6 Summary of code and standards and their influence

The codes and standards have relatively low impact on the changes in our design. The revisions are for the functionality of the deflector. If the revision included a material change, the standards may be useful. However, the material has not been impacted by the changes informed by this engineering analysis.

5.3 RISK ASSESSMENT

5.3.1 Risk Identification

There are a few risks that we need to mitigate in our design. The first of these is our Solidworks design. We initially drafted all our parts in AutoCAD, which was difficult to convert for 3D printing. Another risk for us is 3D printing. We are trying to minimize the size of our design, but we need to balance this with print time and the machine's resolution. There is a decent chance if we design our brush too small, the parts won't maintain the necessary clearances for proper assembly and usage. The last issues relate to the filaments in our brush. There was a risk that the filaments wouldn't be stiff enough to clean a vessel when fully extended. There is also a chance that the filaments we ordered won't arrive in time for our prototype.

5.3.2 Risk Impact or Consequence Assessment

The Solidworks drafting is a minor risk because the impact and likelihood of this occurring are very low. The 3D printing issues could have a very severe impact. Each print of our parts takes hours to complete, so the number of redesigns and prints we are able to test is limited. If we are not able to get the clearances for our required size, our prototype will not achieve our goal of easy production. The filament stiffness issue is probably the most significant risk we face. This is because we have very limited options for the size and material of our filaments because we are purchasing a relatively small quantity. If the filaments we order are too stiff or too flexible, we won't have time to find replacements

5.3.3 Risk Prioritization

Our prioritization of risks is as follows:

1. Filament stiffness
2. 3D printing issues
3. Filaments arriving
4. Solidworks design.

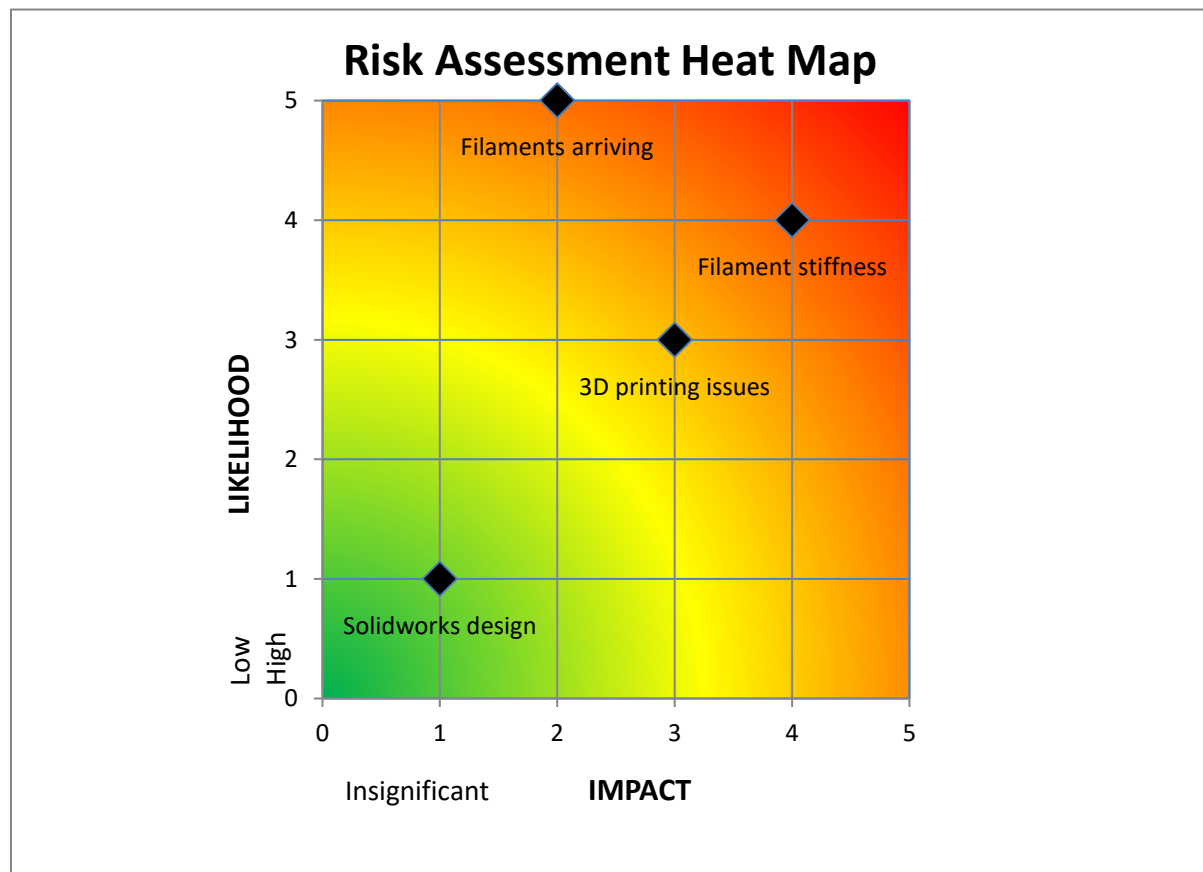


Fig. 20 The heat map used to visualize the risk posed by a problem based on impact and likelihood

After identifying these risks, we made a plan to help us control or eliminate them. For the filament stiffness, we created a SolidWorks motion model to test the filament deflection when fully extended. This was done by modelling the filament with both an applied force and gravitational force acting on it.

This was repeated for multiple filaments of different sizes and materials. We ordered our filaments as soon as we completed our Solidworks analysis to try to ensure a timely arrival. For 3D printing issues, we started our design larger than desired and only printed critically interlocking pieces. This allowed us to determine the required clearances without reprinting our full design each time, ultimately saving us time. We also started this process early to allow for as many modifications or reprints as necessary. Similarly, we redrafted our initial designs into Solidworks early in the process to give ourselves time to get accustomed to the interface and make modifications as needed.

6 WORKING PROTOTYPE

6.1 A PRELIMINARY DEMONSTRATION OF THE WORKING PROTOTYPE

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6.2 A FINAL DEMONSTRATION OF THE WORKING PROTOTYPE

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6.3 AT LEAST TWO DIGITAL PHOTOGRAPHS SHOWING THE PROTOTYPE

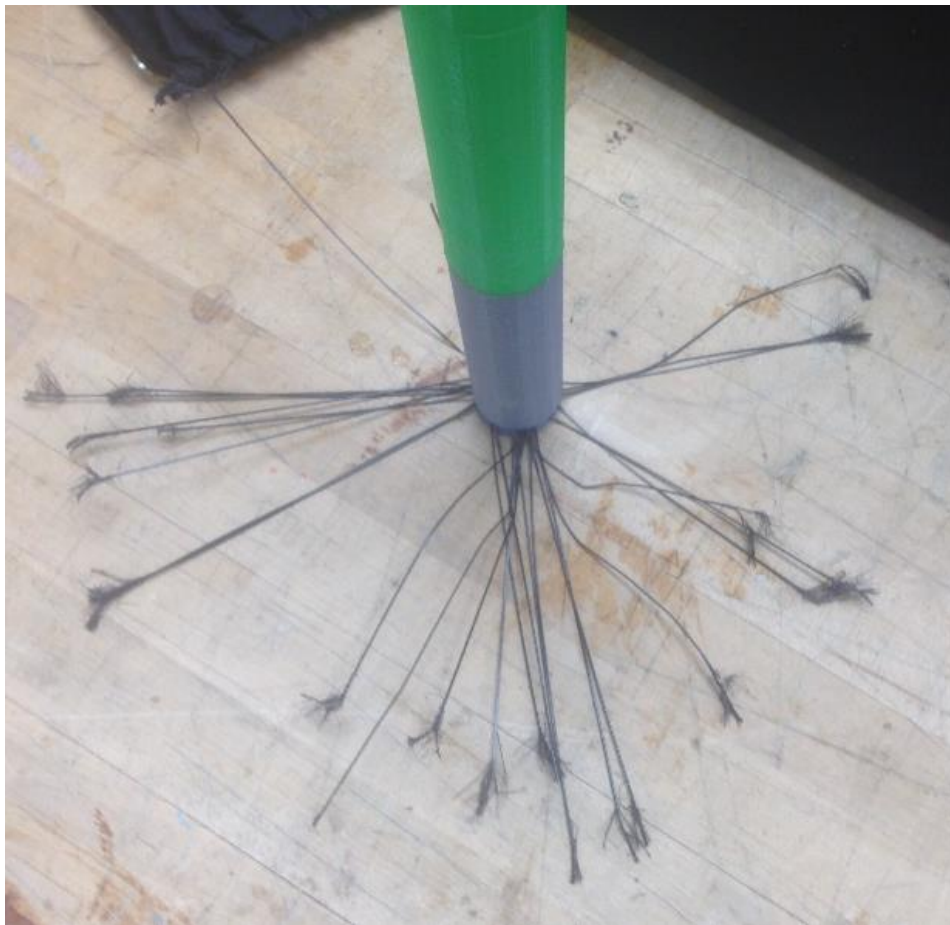


Fig. 21 This image shows the maximum reach of the first prototype. The reach of this brush was measured to be around 9.5 to 10 in.

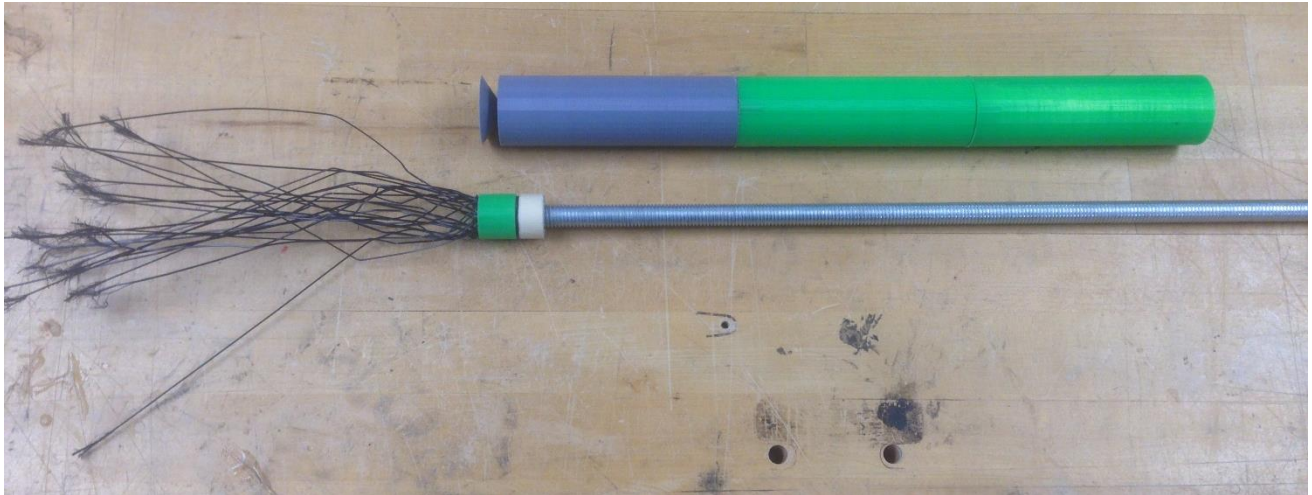


Fig. 22 *The two pieces of our brush are shown above. The top piece is the outer sleeve, which has a height of just over 15 in. and a width of 1.5 in. The lower piece is our brush head and handle. This design is completely removable and makes the product easy to wash by hand or in a dishwasher*

6.4 A SHORT VIDEOCLIP THAT SHOWS THE FINAL PROTOTYPE PERFORMING

A link to our prototype cleaning our test vessel (the wine decanter) is posted below. The decanter was wetted and filled with various sawdust and debris.

<https://www.youtube.com/watch?v=GkFxnubMALs>

There are some key things to point out from this video. First, when the brush is fully splayed out, the bristles easily reach the outer walls of the decanter. We measured the maximum reach of this first prototype to be between 9.5 and 10 in. This is significantly farther than any brushed currently on the market. The versatility of the brush is also shown. At one point in the video you can see the bristles are contracted for a smaller reach. This allowed the brush to easily clean the lower lip of the decanter used. The brush is then easily contracted and removed from the vessel.

Our first prototype was successful in the fact that it was able to extend as designed and easily clean most of the vessel. However, we noticed that the upper portion of the decanter base was hard to clean with our current design. An image of the hard to clean area is specified in Fig. 23.



Fig. 23 The hardest area for the current brush to reach is outlined in orange. Some debris can still be seen on this portion of the decanter

Based on this test, we realized there was a need to redesign our deflector. We also want to continue to decrease the diameter of our outer sleeve. This would allow the user more space to tilt the brush once inside the vessel, allowing it to more easily clean the hard to reach areas. The filaments could also be improved. We think that having slightly stiffer filaments and a greater filament density for the brush would improve the cleaning ability of our brush completely. The last change we would like to implement is to add a sponge or scrubbing pad to the base of the brush's deflector. This would allow the brush to be used as an extended scrubbing tool, making it easy to clean the base of the vessel.

6.5 PHOTOGRAPHS SHOWING THE SECOND PROTOTYPE (DEFLECTOR REDESIGN)

The three redesigned deflector are shown in Fig. 23A below.



Fig. 23A The three redesigned deflector are picture here. The middle deflector will be used with a redesigned outer sleeve, while the other two fit into our first prototype's outer sleeve.

The first design shown (far left) is a modification of our first deflector. Half of the original surface is unchanged. Around the edge of the other half, we added ramps that will redirect the bristles upward. This will give our brush two different angles of deflection to clean at, which would allow it to reach the upper and lower portions of a vessel simultaneously. There are also sidewalls added to keep the bristles partitioned during the cleaning process. This will ensure that the both of the deflection types will have bristles at all times. One risk for this design is having two extreme angles of deflection and not being able to reach the area between them. This redesign seems to have the most potential currently.

The second design (middle) is a completely new deflector. Unlike our initial design, this deflector will be attached to the outside of the outer sleeve. The brush is then operated in the same way as the first prototype. The advantage of this deflector is that it would allow us to minimize the size of our brush because we would no longer need to work about clearances for the deflector's tab. The downside of this design is that it becomes much hard to get the bristles to deflect well, so the curvature on the topside of the deflector is critical and will require tedious adjustments and testing.

The third design (far right) was the simplest redesign. We decreased the original deflector's angle from 35° to 20°. The idea behind this is that it will allow the bristle to be directed outward at a sharper angle, allowing the bristles to reach across perpendicular to the base. This design resulted in a slight improvement in the brushes performance, but it did not get the brush to perform to our satisfaction.

Below are four images of the prototype and our most successful redesigned deflector.



Fig. 24 This image shows the first prototype brush extended within our test vessel. The bristles easily reach the outer edge of the test vessel.



Fig. 25 Decreasing the difference between the inner and outer diameters of the sleeve will allow us to greatly reduce the overall size of our brush.



Fig. 26 The first prototypes filaments were hand threaded through our brush head.



Fig 27 One of the redesigned deflectors. The raised lips are shown in this image. The height of these lips will likely need to be increased to get the desired performance.

7 DESIGN DOCUMENTATION

7.1 FINAL DRAWINGS AND DOCUMENTATION

7.1.1 Engineering drawings

Deflector Piece

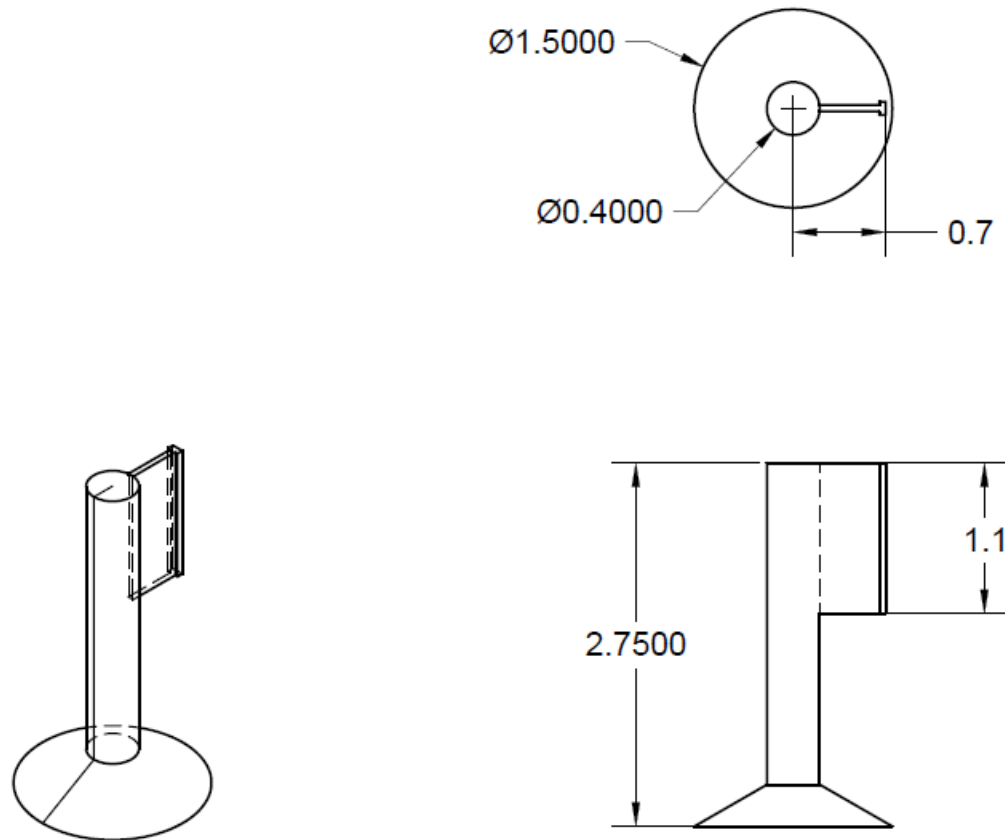


Fig. 28 *The deflector used in the prototype*

Bristle Handle Drawing

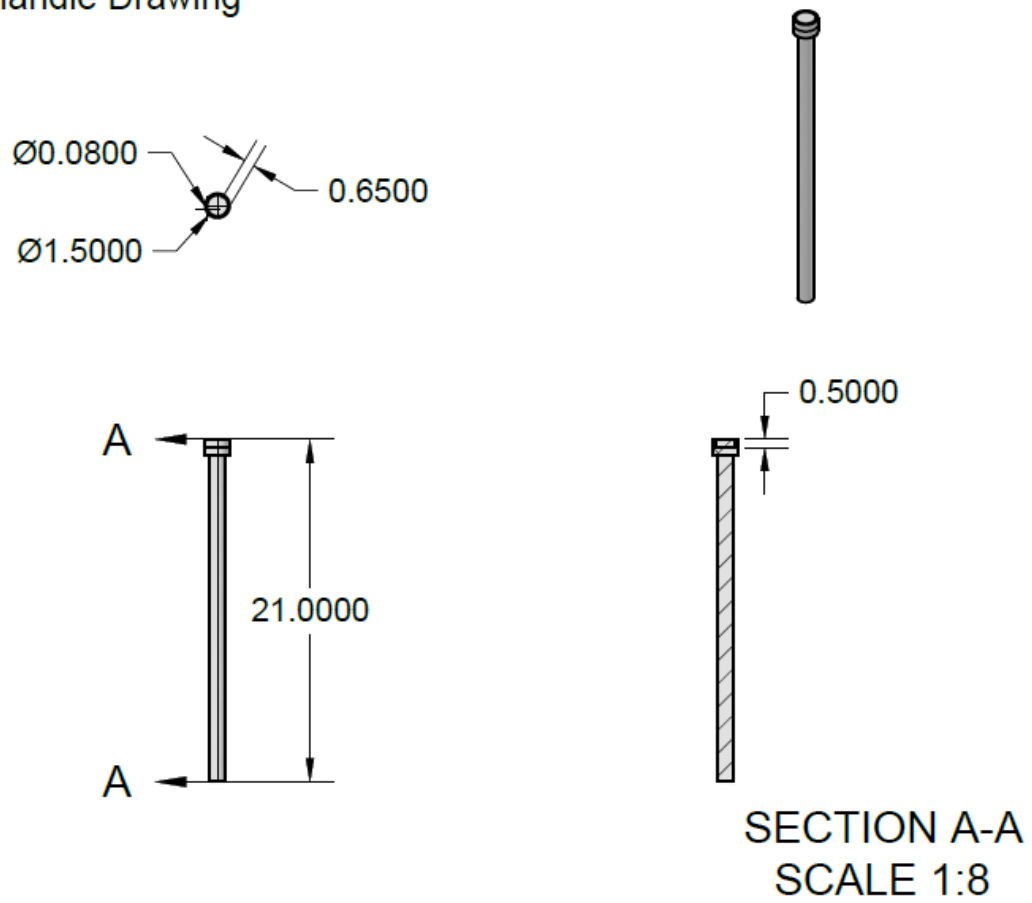


Fig. 29 The handle and head used to move the brush downwards

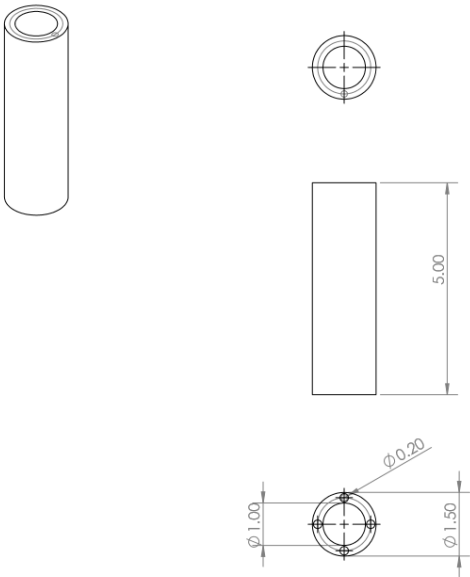


Fig. 30 Top piece of the sleeve

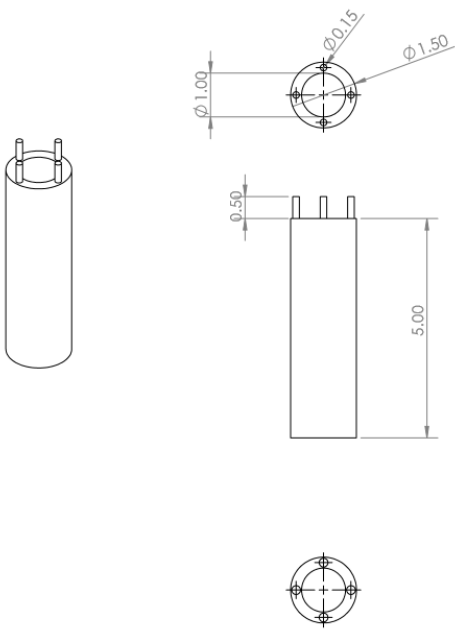
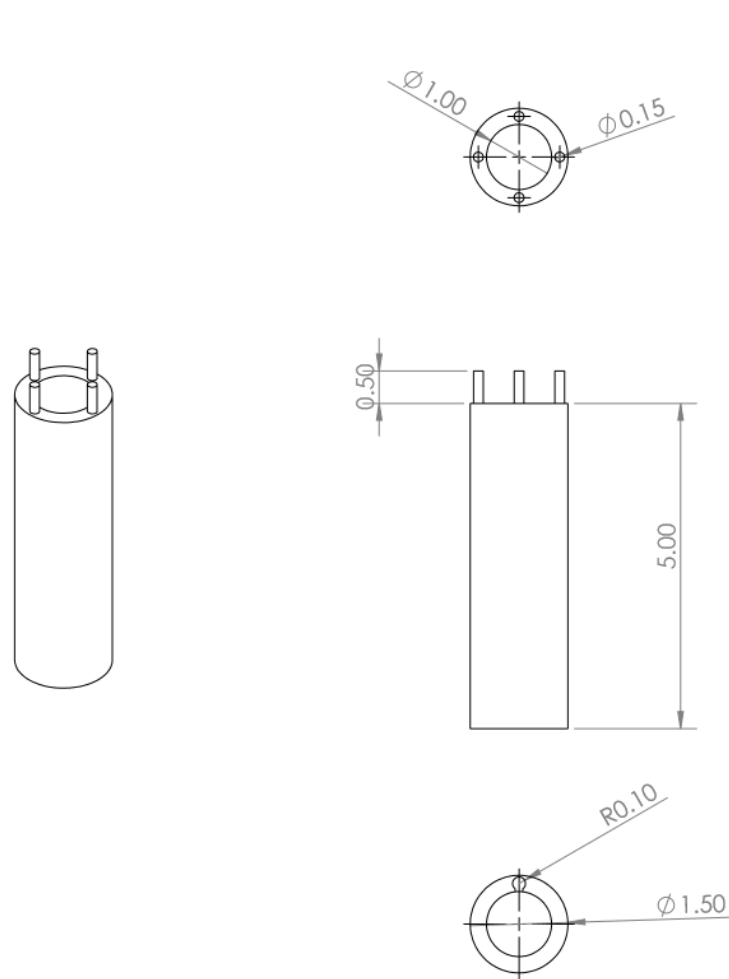


Fig. 31 The mid piece of the sleeve

*Fig. 32**The bottom piece of the sleeve that attaches to the deflector*

7.2 FINAL PRESENTATION

7.2.1 A live presentation in front of the entire class and the instructors
N/A

7.2.2 A link to a video clip

This is a video of the final presentation slide show for the external review board.

<https://youtu.be/iAf3T6h1Mtk>

7.3 TEARDOWN

The work place has been cleaned up and the prototypes have been taken home with the group. Evidence of this can be seen below in Fig. 33

TEARDOWN TASKS AGREEMENT

PROJECT: H NAMES: Michael Romo INSTRUCTOR: Aaron Hall

The following teardown/cleanup tasks will be performed:

- Cleared work area
- Took prototype home

Instructor comments on completion of teardown/cleanup tasks:

Group H

Instructor signature: Mary Walast Print instructor name: MARY WALAST

Date: 12/9/16

(Group members should initial near their name above.)

Fig. 33 The completed teardown form

8 DISCUSSION

8.1 USING THE FINAL PROTOTYPE PRODUCED TO OBTAIN VALUES FOR METRICS, EVALUATE THE QUANTIFIED NEEDS EQUATIONS FOR THE DESIGN. HOW WELL WERE THE NEEDS MET? DISCUSS THE RESULT.

| Metric Number | Associated Needs | Metric | Units | Min Value | Max Value | Actual Value | Normalized Value |
|---------------|------------------|------------------|----------|-----------|-----------|--------------|------------------|
| 1 | 3, 5 | Diameter | mm | 10 | 25 | 25 | -1.000 |
| 2 | 3, 5 | Length | mm | 150 | 300 | 200 | 0.333 |
| 3 | 1, 2 | Food Safe | Binary | 0 | 1 | 1 | 1.000 |
| 4 | 3, 4, 5 | Cleaning Ability | Scale | 1 | 5 | 3.5 | 0.625 |
| 5 | 5 | Cleaning Time | Sec. | 5 | 300 | 120 | -0.390 |
| 6 | 1, 2 | Cost | USD (\$) | 1 | 150 | 70 | -0.463 |
| | | | | | | TOTAL | 0.105 |

Table 2 The predictive metric evaluation for the expandable brush

| Metric Number | Associated Needs | Metric | Units | Min Value | Max Value | Actual Value | Normalized Value |
|---------------|------------------|------------------|----------|-----------|-----------|--------------|------------------|
| 1 | 3, 5 | Diameter | mm | 10 | 25 | 25 | -1.000 |
| 2 | 3, 5 | Length | mm | 150 | 300 | 300 | 1.000 |
| 3 | 1, 2 | Food Safe | Binary | 0 | 1 | 1 | 1.000 |
| 4 | 3, 4, 5 | Cleaning Ability | Scale | 1 | 5 | 3.5 | 0.625 |
| 5 | 5 | Cleaning Time | Sec. | 5 | 300 | 20 | -0.051 |
| 6 | 1, 2 | Cost | USD (\$) | 1 | 150 | 60 | -0.396 |
| | | | | | | TOTAL | 1.178 |

Table 3 The actual metric evaluation for the expandable brush prototype

We selected the expandable brush design to be the alternative that we pursued. Its original score when we were estimating its evaluation metrics was 0.105. After evaluating our prototype, it was scored at 1.178. We were accurate in predicting its diameter, food safeness, and its cleaning ability. However, we overestimated the cleaning time and cost. The cost was lower, because most of it was 3D-printed for free. Most of the cost of the design was for test vessels and materials that ended up failing. The total cost of material that went into the prototype cost about \$10. Another flaw in our prediction was that we underestimated the possible length of the expandable brush. By shortening the length of the deflector hand sketched in Fig. 7, which imposed a height limit, we could make the length of the prototype as large as we wanted. Realistically, the brush bristle and handle sizes limited the maximum height, but this maximum height was far greater than any application the prototype could be used for. The big takeaway from this metric evaluation is the fact that our prototype can clean a taller vessel more quickly than anticipated and cost less results in the drastic increase in its evaluation score.

A major area for improvement is the ability for the bristles to reach upwards and clean the upper surface. While this may not be necessary for wine decanters, since they generally don't get stains on the bottom, the brush needs to reach upwards with its bristles if it is to be able to clean a variety of vessels. To address this we have developed new prototypes for the bristle deflector seen in section 6. In addition, we hope to try a new material for the bristles that is more rigid and will deflect perpendicularly outwards more easily. Discussion of possible improvements can be read about in detail in section 6.

8.2 DISCUSS ANY SIGNIFICANT PARTS SOURCING ISSUES? DID IT MAKE SENSE TO SCROUNGE PARTS? DID ANY VENDOR HAVE AN UNREASONABLY LONG PART DELIVERY TIME? WHAT WOULD BE YOUR RECOMMENDATIONS FOR FUTURE PROJECTS?

The straight PLA filaments from JPSON did not arrive on time for our prototype. Fortunately, we had a contingency plan to gather nylon brush filaments from a broom that we had acquired. These nylon filaments weren't as stiff as we would have liked, but were frayed at the end which enhanced its cleaning ability. I would recommend that future projects investigate Chinese shipping times more, they were not correct in our case. Additionally, I would have contingency parts and plans for most areas of the design in the case that something gets lost, destroyed, or is delivered late.

8.3 DISCUSS THE OVERALL EXPERIENCE:

8.3.1 Was the project more or less difficult than you had expected?

The project was far more difficult than expected. Our group realized this while brainstorming possible ideas to work on. It was difficult to settle down on a single problem that we wanted to solve. This brainstorming required far more work than we thought. The other portion that we found challenging was designing the minutia of the prototype and revising it based on tests. The minutia was characterized primarily by part clearances and deflector angles. Creating, testing, and revising these was much more time consuming and difficult than expected. Finally, working on our final SolidWorks model that displays the brush filaments getting splayed out when contacting a deflector was extremely hard. Even with the coarsest mesh settings, running a nonlinear static study of the system is too great for a School of Engineering computer to handle. Future projects should keep in mind that honing the scope of the problem, improving the small pieces of the project, and complex SolidWorks models are likely to be tasks which make the project more difficult than expected.

8.3.2 Does your final project result align with the project description?

The expandable brush does fulfill the project description. It can be inserted into a vessel with a small neck of 1.5 in. with a large complex base and expand up to 10 in. in diameter. It was able to clean every surface inside the wine decanter that we evaluated its performance with, except the upper wall. As discussed in the prototype section, we have proposed some redesigns to be able to reach upwards and clean the upper walls of the decanter. Wine decanters rarely get stained on the upper surface, but to make our design applicable to many other vessels that do get stained on the upper surface. On balance, our expandable brush proved the design concept and description that we desired to investigate this semester and we have identified the next goal to fully improve its performance.

8.3.3 Did your team function well as a group?

Despite only having 2 members, our group functioned well and was very productive. Our class schedules did not optimally align, which posed a small issue. However, both of us were willing to make sacrifices for the success of the project. The possibility of eventually have intellectual property of our own motivated both of us to make progress throughout the semester.

Our personalities complimented each other well too. Having both taken the leadership course in the School of Engineering, we thought it important to know our Myers-Briggs and Enneagram types. Michael

is an ISTJ and Enneagram type 5. These types indicate that Michael is alert, insightful, and curious. He works very well alone and with people, but under stress can isolate himself too much [A]. Aaron on the other hand is an ENTJ and Enneagram type 7. These types indicate that Aaron is high-spirited, practical, and a good leader. It also shows that he prefers working in a group. Under stress, he can take on too much and overextend himself. Together, our team balanced each other out with Michael's intense focus and Aaron's practicality and sense of direction. In addition to having complimentary personalities, the members of the team have worked together since the first semester of freshman year. This long professional history provided the other insights into the other's tendencies and how to optimize their performance under stress.

Any disadvantage posed by having only two members was overcome with a combination of motivation, personality agreement, and professional history. With these strengths, we were able to know exactly what type of project we wanted to tackle. We wanted to develop a product that solved a common problem with a clever answer. We focused on choosing a product that would benefit from our strengths. Eventually, we settled on developing a product for cleaning vessels with small openings and large complex bases.

8.3.4 Were your team member's skills complementary?

In addition to this collective motivation, our skills complimented each other well. We believe that together we are the perfect mechanical engineer. Michael Roznik's proficiency with solid works along with Aaron Hall's hand drawn designs proved to be an ideal combination for prototyping. Both of us were not only good with technical communication among ourselves, but we excelled at verbal communication and PowerPoint presentations. Our ability to communicate to the course directors and judges at the External Review Board Presentation positively impacted the outcome of our product.

8.3.5 Did your team share the workload equally?

While each member of the team performed a different set of duties, the workload was shared equally. Aaron generally came up with general designs and together with Michael the ideas were refined. Michael was the most proficient with AutoCAD and SolidWorks, so he did most of the drafting. Presentation workloads were shared exactly equally. Both of us would give each other critiques on what to improve whether it was content or speaking style. In the case of sharing the workload, having only two members was advantageous. The low number of members meant that to get the amount of work done that was required, everyone had to pitch in. Each due date was characterized by an "all hands on deck" mentality.

8.3.6 Was any needed skill missing from the group?

Originally a few skills were missing from the group, since we only had two people. However, we overcame this by working together to learn the necessary skills. Our lack of skill was our collective unfamiliarity with part drafting on SolidWorks, since both of us had been trained on Solid Edge software. It took about two and a half weeks for us to be comfortable on the software. Simulating the bristles splaying out was still difficult for us. However, even with the help of course instructors the static nonlinear SolidWorks simulation would not run properly. The other hurdle that our team encountered skill-wise was our knowledge of 3D printing. With the help of instructors and teaching assistants we learned how to print and do it efficiently.

8.3.7 Did you have to consult with your customer during the process, or did you work to the original design brief?

We worked to the original design brief. This was possible, because we did an excellent job at defining the scope of our project. It was precise enough to have a clear set of evaluation metrics, but fulfilled a broad enough need to be a versatile product. One of the judges foresees our product being useful in the craft and home brewing industry to clean a type of processing canister. For applications like this a full market study will be required and then we must meet one on one with customers interested in purchasing it for various applications. The design can be altered to cater to their specific needs.

8.3.8 Did the design brief (as provided by the customer) seem to change during the process?

The design brief remained constant since the scope of our project was well defined early on.

8.3.9 Has the project enhanced your design skills?

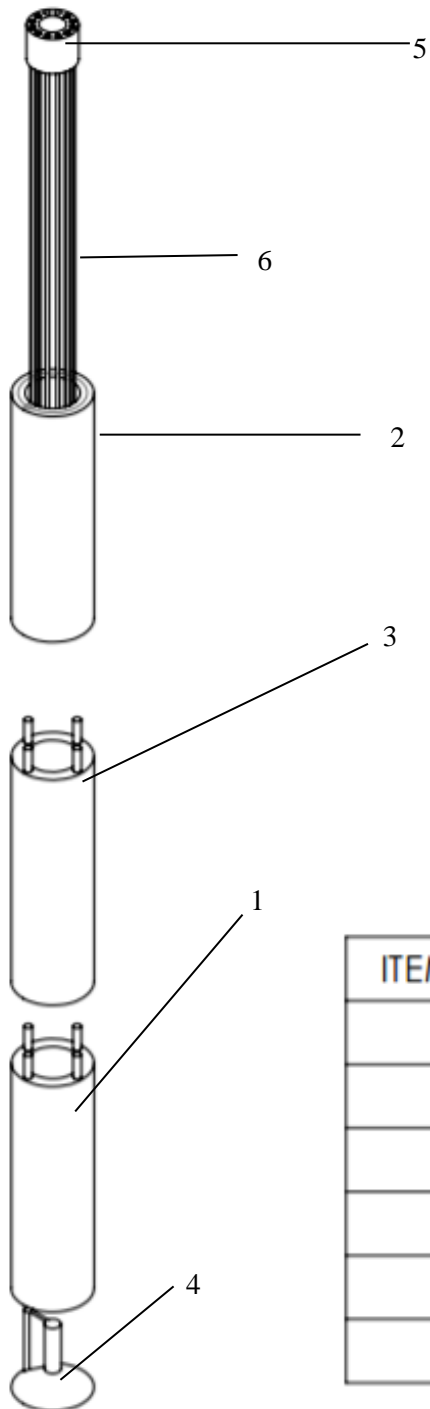
As previously discussed in section 8.3.6, our knowledge of SolidWorks for design and analysis has greatly increase along with our ability to create accurate hand sketches and 3D print. Having a real project that we decided ourselves has been extremely beneficial for our general design skills. In fact with these enhanced skills, our group plans on continuing work on the project next semester.

8.3.10 Would you now feel more comfortable accepting a design project assignment at a job?

We would both be more confident in our ability to solve a problem with a design that we have scoped and generated ourselves. This is semester has been very useful in not only developing our design skills, but also growing our confidence so that we can accept new projects in our future careers. This project has taught us how to adapt our designs to new challenges and build solutions to real world problems. With this experience under our belts, we feel ready to accept a design project assignment in our next jobs.

8.3.11 Are there projects that you would attempt now that you would not attempt before?

Neither of us had ever attempted a product development project before. Aaron had worked on small and large scale projects at a petrochemical company last summer. Michael had optimization projects for an industrial food production company. Neither of us had any experience developing a product, but thought it would be a good experience to try for senior design. Now, both of us would readily accept a product development project. We liked developing this product so much this semester that we intend to continue work on our expandable brush next semester.

9 APPENDIX A – PARTS LIST

| ITEM NO. | PART NUMBER | QTY. |
|----------|--------------|------|
| 1 | Sleeve Base | 1 |
| 2 | Sleeve End | 1 |
| 3 | Sleeve Mid | 1 |
| 4 | Deflector | 1 |
| 5 | Brush Head | 1 |
| 6 | PET Filament | 12 |

10 APPENDIX B - BILL OF MATERIALS

| Part | Source | Model No./Name | Quantity | Unit Cost |
|----------------|-------------------------|-----------------|----------|-------------------------|
| Sleeve | 3D Printer | NA | 1 | 0 (if printed at WUSTL) |
| Deflector | 3D Printer | NA | 1 | 0 (if printed at WUSTL) |
| Bristle handle | 3D Printer | NA | 1 | 0 (if printed at WUSTL) |
| Brush bristles | Alibaba | Nylon filaments | 350 | \$1.50/kg |

11 SOLID WORKS REPORT ON SINGLE BRUSH FILAMENT



DESCRIPTION

This is a static deformation and stress test of a PET filament that will be used as a brush bristle in the expandable brush project for MEMS 411

Simulation of PET Filament 2

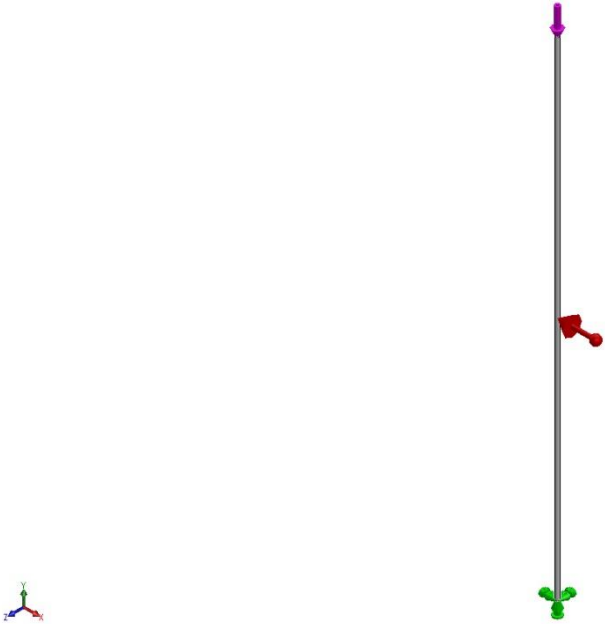
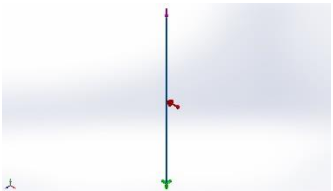
Date: Thursday, December 08, 2016
Designer: Aaron Hall and Michael Roznik
Study name: Static 1
Analysis type: Static

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| Connector Definitions | Error! Bookmark not defined. |
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ASSUMPTIONS

MODEL INFORMATION

|  <p>Model name: PET Filament 2 Current Configuration: Default</p> | | | |
|---|------------|---|--|
| Solid Bodies | | | |
| Document Name and Reference | Treated As | Volumetric Properties | Document Path/Date Modified |
| Boss-Extrude1  | Solid Body | Mass:0.00171646 lb Volume:0.0334587 in ³ Density:0.0513008 lb/in ³ Weight:0.00171529 lbf | H:\My Documents\Senior Fall\PET Filament 2.SLDPRT Nov 14 21:51:19 2016 |

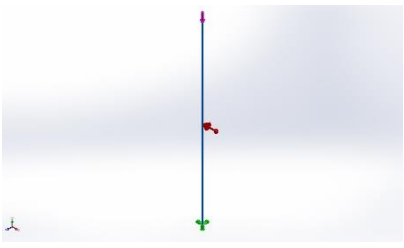
STUDY PROPERTIES

| | |
|---|---|
| Study name | Static 1 |
| Analysis type | Static |
| Mesh type | Solid Mesh |
| Thermal Effect: | On |
| Thermal option | Include temperature loads |
| Zero strain temperature | 298 Kelvin |
| Include fluid pressure effects from SOLIDWORKS Flow Simulation | Off |
| Solver type | FFEPlus |
| Inplane Effect: | Off |
| Soft Spring: | Off |
| Inertial Relief: | Off |
| Incompatible bonding options | Automatic |
| Large displacement | On |
| Compute free body forces | On |
| Friction | Off |
| Use Adaptive Method: | Off |
| Result folder | SOLIDWORKS document (H:\My Documents\Senior Fall) |

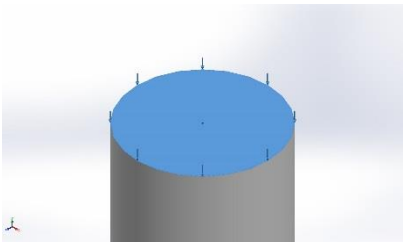

UNITS

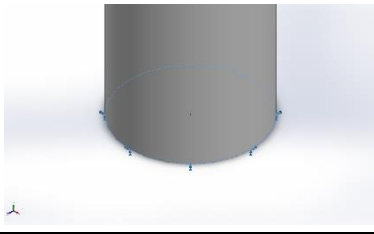
| | |
|----------------------------|---------------|
| Unit system: | English (IPS) |
| Length/Displacement | mm |
| Temperature | Kelvin |
| Angular velocity | Rad/sec |
| Pressure/Stress | psi |

MATERIAL PROPERTIES

| Model Reference | Properties | Components |
|---|--|---|
|  | Name: PET Model type: Linear Elastic Isotropic Default failure criterion: Unknown Tensile strength: 8310.66 psi Compressive strength: 13474 psi Elastic modulus: 429312 psi Poisson's ratio: 0.37 Mass density: 0.0513008 lb/in^3 | SolidBody 1(Boss-Extrude1)(PET Filament 2) |
| Curve Data:N/A | | |

LOADS AND FIXTURES

| Load name | Load Image | Load Details |
|-----------|---|--|
| Force-1 |  | Entities: 1 face(s) Type: Apply normal force Value: 0.01 N |
| Gravity-1 |  | Reference: Right Plane Values: 0 0 -386.22 Units: English (IPS) |

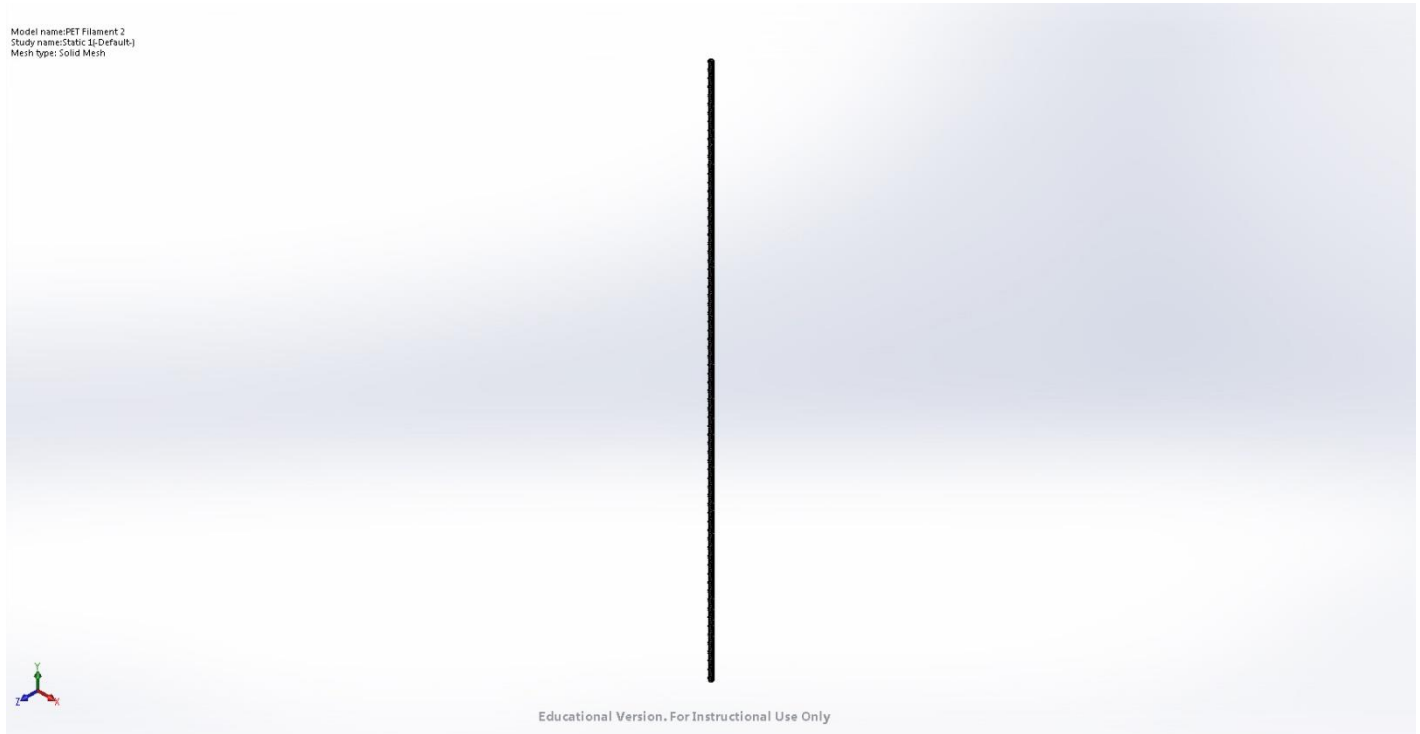
| Fixture name | Fixture Image | Fixture Details | | |
|-------------------------|---|---|--------------|------------|
| Fixed-1 |  | Entities: 1 face(s) Type: Fixed Geometry | | |
| Resultant Forces | | | | |
| Components | X | Y | Z | Resultant |
| Reaction force(lbf) | 0.00171427 | 0.00223063 | 1.71516e-006 | 0.00281326 |
| Reaction Moment(lbf.in) | 0 | 0 | 0 | 0 |

MESH INFORMATION

| | |
|---------------------------------|---------------|
| Mesh type | Solid Mesh |
| Mesher Used: | Standard mesh |
| Automatic Transition: | Off |
| Include Mesh Auto Loops: | Off |
| Jacobian points | 4 Points |
| Element Size | 0.026194 in |
| Tolerance | 0.0013097 in |
| Mesh Quality | High |

MESH INFORMATION - DETAILS

| | |
|--|-----------|
| Total Nodes | 26295 |
| Total Elements | 14593 |
| Maximum Aspect Ratio | 3.7747 |
| % of elements with Aspect Ratio < 3 | 99.9 |
| % of elements with Aspect Ratio > 10 | 0 |
| % of distorted elements(Jacobian) | 0 |
| Time to complete mesh(hh:mm:ss): | 00:00:03 |
| Computer name: | URB218-26 |
| | |



RESULTANT FORCES

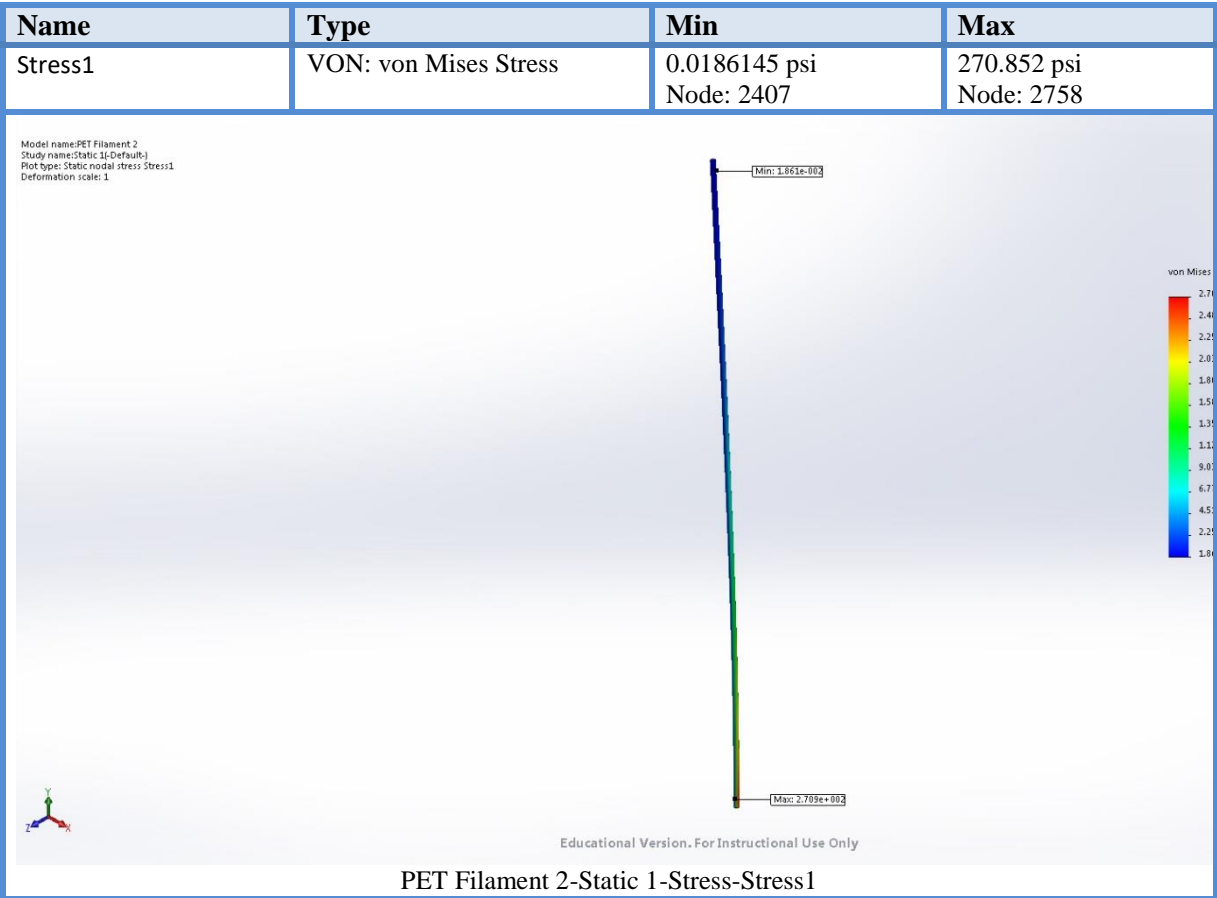
REACTION FORCES

| Selection set | Units | Sum X | Sum Y | Sum Z | Resultant |
|---------------|-------|------------|------------|--------------|------------|
| Entire Model | lbf | 0.00171427 | 0.00223063 | 1.71516e-006 | 0.00281326 |

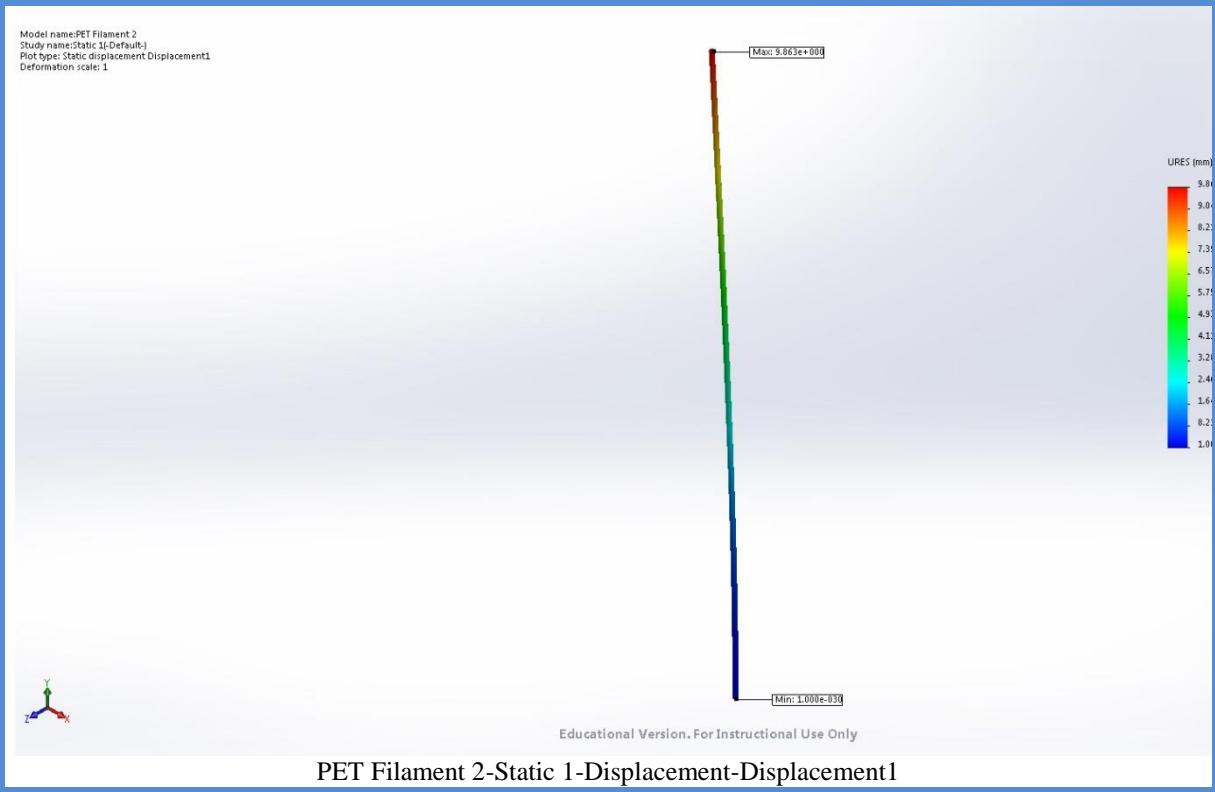
REACTION MOMENTS

| Selection set | Units | Sum X | Sum Y | Sum Z | Resultant |
|---------------|--------|-------|-------|-------|-----------|
| Entire Model | lbf.in | 0 | 0 | 0 | 0 |

STUDY RESULTS



| Name | Type | Min | Max |
|---------------|------------------------------|-------------------|---------------------------|
| Displacement1 | URES: Resultant Displacement | 0 mm Node: 348 | 9.86323 mm Node: 26293 |



| Name | Type | Min | Max |
|---------|--------------------------|--------------------------------|------------------------------|
| Strain1 | ESTRN: Equivalent Strain | 8.87462e-008 Element: 10958 | 0.000473247 Element: 2374 |

